

Advanced and Intelligent Manufacturing in China

Weimin Yang · Ranran Jian

Polymer 3D Printing and 3D Copying Technology



Chemical Industry Press Co., Ltd.



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Advanced and Intelligent Manufacturing in China

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Preface

The manufacturing industry is the mainstay of the national economy and is the foundation of the country, the instrument of its prosperity, and the basis of its strength. In the past decade, China's manufacturing industry has continued to develop rapidly, its comprehensive strength has been enhanced, its international status has been greatly enhanced, and it has become the largest manufacturing country in the world. However, China is still in the process of industrialization, and the problem of large but not strong is prominent, and there is a large gap compared with advanced countries. In order to solve the problem of large but not strong manufacturing industry, weak independent innovation capability, high dependence on key core technologies and high-end equipment, the State Council released the national plan of "Made in China 2025" on May 8, 2015. Subsequently, the Ministry of Industry and Information Technology released the "Made in China 2025" plan, which put forward the "three-step" development strategy of China's manufacturing industry and the goals, guidelines, and strategic lines for 2025, and formulated nine strategic tasks and ten key development areas. On August 19, 2016, the Ministry of Industry and Information Technology, the Development and Reform Commission, the Ministry of Science and Technology, and the Ministry of Finance jointly released the "Made in China 2025" manufacturing innovation center, industrial foundation, green manufacturing, intelligent manufacturing, and high-end equipment innovation five project implementation guidelines.

In response to the major strategic deployment made by the Party Central Committee and the State Council to build a strong manufacturing country, governments, enterprises, and scientific research departments all over the world are actively exploring and deploying. Accelerating the development of the integration of new generation information technology and manufacturing technology, promoting the transformation of China's manufacturing mode from "Made in China" to "Made in China," and accelerating the transformation of China's manufacturing industry from big to strong, is becoming our new historical mission. At present, the process of information revolution continues to evolve rapidly, and technologies such as Internet of Things, cloud computing, big data, and artificial intelligence are widely penetrated in various fields of economy and society, and the prosperity of information economy has become an important symbol of national strength. Technologies in the fields of

additive manufacturing (3D printing), robotics and intelligent manufacturing, control and information technology, artificial intelligence and other areas continue to make major breakthroughs, pushing the traditional industrial system to differentiate and change, and will reshape the international division of labor in manufacturing. The integration and development of manufacturing technology with the Internet and other information technology have become a major trend and the main feature of the new round of scientific and technological revolution and industrial change. Against this background of great development and change in China's manufacturing industry, Chemical Industry Publishing House has taken the initiative to follow the development trend of technology and industry and organized the publication of the "Made in China 2025" publication project series, which is a courageous and timely initiative.

The "Made in China 2025" publication project is a series of books closely focused on the "Made in China 2025," the action program of the first decade of the implementation of the manufacturing power strategy issued by the State Council. It is a set of high-level and original academic monographs. Based on the two major fields of intelligent manufacturing and equipment, control and information technology, the series covers a series of core technologies such as Internet of Things, big data, 3D printing, robotics, intelligent equipment, industrial cyber security, knowledge automation, and artificial intelligence. The selection plan of the series is closely integrated with the "Made in China 2025" plan and 11 supporting implementation guides, action plans or special plans, and the content of each fascicle is organized for some core technologies in each field, focusing on the technological development achievements in the domestic manufacturing industry, aiming to strengthen the research and development, promotion and application of advanced technologies, and provide a platform for It aims to strengthen the R&D, promotion and application of advanced technologies, providing targeted directional guidance and systematic technical reference for the implementation of the "Made in China 2025" action program.

The set focuses on the following key features.

First of all, the contents of the series are striving for originality, with networked and intelligent technology as the core, bringing together many cutting-edge technologies, reflecting some of the latest technological achievements at home and abroad, especially the relevant original technological achievements in China are reflected. These books contain many new technologies that have won many national and provincial science and technology awards, and the publication of the books is very helpful to the promotion and application of new technologies! These contents not only solve practical problems for technical personnel, but also provide new directions and expand new ideas for research.

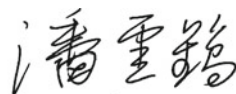
Secondly, while introducing new technologies, theories, and methods in the corresponding professional fields, each fascicle of the series gives priority to new technologies with application prospects and examples of their promotion and application, so as to promote the transformation of outstanding scientific research results into industry.

The series is led by Youxian Sun, an academician of control engineering in China, who is the director of the editorial committee; Cheng Wu, Tianran Wang, Nanning Zheng, and many other academicians participate in the planning and organizing work;

many middle-aged and young scholars, such as Changjiang scholars, Jieqing, and Youqing, participate in the specific writing work, which has a high academic level and writing quality.

It is believed that the publication of this series is of positive significance to promote the implementation of the national strategic plan of “Made in China 2025,” which can effectively promote the R&D and innovation of China’s intelligent manufacturing technology, promote the technological transformation and upgrading of the equipment manufacturing industry, improve the design capability and technology level of products, and thus enhance the core competitiveness of China’s manufacturing industry from multiple angles. The core competitiveness of China’s manufacturing industry.

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About This Book

This book innovatively introduces the concept of polymer 3D copying technology, introduces the two technologies of polymer 3D printing and 3D copying by analogy, and elaborates on the core principle and process of polymer 3D copying technology, the composition, basic parameters, and structural design of polymer 3D copying machine, the precision control method of polymer 3D copying products, the mechanism of defects and solutions, in addition to discussing the development trend of polymer 3D copying technology. The development trend of polymer 3D copying technology is also discussed.

The book takes both traditional and new materials, novel contents, focuses on theory and practicality and takes into account the needs of both academic reference and industrial applications in the chapter structure, reflecting the contents and applications of polymer 3D printing and 3D copying technology in a more systematic way, which can be read and referred by engineers and technicians, R&D personnel and teachers and students of related majors engaged in polymer processing.

Всё для победы! **НАРОДНЫЙ
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Introduction

3D printing technology, first called additive manufacturing technology, was born in the late 1980s as a high-tech manufacturing technology based on the material stacking method. After the concept of “3D printing” was introduced, it led to a new understanding of additive manufacturing technology. The popularity of multidisciplinary cross-knowledge has also led to rapid development of additive manufacturing technology. Drawing on such a successful example, we proposed the concept of “3D copying” based on molding. Based on virtual design or 3D scanning modeling of target products, intelligent planning of mold structure, 3D printing, and intelligent injection molding, the “3D copy” technology is expected to become a new trend in the intelligent development of modern manufacturing industry and has a broad application prospect.

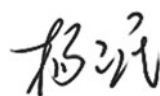
3D copying technology dates back as far as the Bronze Age, even before the advent of two-dimensional paper printing. More than 3000 years ago, humans began to use molds to make large bronze works such as the Bronze Standing Man, the Four Sheep Square Dignity, and the Hounmuwu Tripod. In the Northern Song Dynasty, Bi Sheng invented the art of movable type printing, carving plates to make “clay movable type,” first made a single character of the Yang text counter script mold, and then according to the manuscript to select the single character, arranged in the word plate, coated with ink printing, after printing and then remove the word mold, set aside for the next printing again. Since the twentieth century, with the rapid development of the manufacturing industry and economic level, molding has become one of the most important processing means in the manufacturing industry with its advantages of high molding efficiency and good product quality.

Focusing on the theme of polymer 3D printing and 3D copying smart manufacturing technology, this book introduces the analogy between 3D printing and 3D copying, integrates the basic research results of polymer precision injection molding and melt micro-segmentation 3D printing technology applications, combines the significant needs and background knowledge of smart manufacturing, innovatively proposes, and initially explores the core principles and technical routes of 3D printing/copying smart manufacturing, and explores three key aspects of scientific and technical problems and solutions. The book consists of six chapters: Chap.

introduces the basic knowledge of the concept, significance and core principles of 3D printing and 3D copying; Chap2 introduces polymer 3D printing and 3D copying processes; Chaps3 and 4 introduce several typical polymer 3D printers and 3D copiers, respectively; Chap5 elaborates on the materials used for polymer 3D copying and their product defect generation mechanisms and solutions; Chap6 the future of polymer 3D copying technology is envisioned and imagined, and several practical development directions are highlighted.

The contents of this book refer to published research papers and technical data at home and abroad, which also include some research results achieved by the author and colleagues in this research field in recent years. The purpose of this book is to help the general readers to understand the theoretical development and technological progress in this field in a more systematic and comprehensive way and to reacquaint themselves with the molding technology with a photocopying concept, hoping to promote the rapid development of polymer molding technology. The team teachers who have made important contributions to the original results of this book include Weimin Yang, Changfeng Guan, Youchen Zhang, Pengcheng Xie, Zhiwei Jiao, Yumei Ding, Hua Yan, Xuetao He, Ying An, Jing Tan, etc. The doctoral students who have directly used the contents of this book as their research topics include Ranran Jian, Baihong Chi, Jian Wang, Panpan Zhang, etc. The master students include Liyang Xie, Fengfeng Liu, Xiaojun Liu, Zhiyun Yan, Bin Du, Yuelin Li, etc. In addition, students involved in the finishing of this book include Li Hu, Yuli Zhang, Xuan Deng, Yanmei Sun, Yujie Song, Haowei Li, Jinfeng Qing, and Siyu Yang.

In the process of writing this book, the author has repeatedly deliberated and changed the draft several times to introduce the knowledge of polymer 3D printing and 3D copying innovation in a systematic and in-depth manner, paying special attention to the needs of both academic reference and industrial applications.



Contents



1 Introduction	1
1.1 Introduction to 3D Printing.....	2
1.1.1 How 3D Printing Works.....	3
1.1.2 History of 3D Printing.....	4
1.1.3 Application of 3D Printing in Polymer Processing and Molding	5
1.2 Introduction to 3D Copying.....	6
1.2.1 How 3D Copying Works.....	6
1.2.2 The Significance of 3D Copying.....	12
1.3 The Difference Between 3D Printing and 3D Copying.....	12
References	15
2 Polymer 3D Printing and 3D Copying Processes.....	17
2.1 Data Acquisition	17
2.2 Data Processing	19
2.2.1 Three-Dimensional Modeling Software	19
2.2.2 Numerical Analysis Software	24
2.2.3 Point Cloud Processing Software.....	29
2.2.4 3D Printing Slicing Software.....	32
2.3 Raw Material Preparation and Plasticization.....	33
2.4 Mold Design and Manufacture [26].....	37
2.5 “Sample Copies”—Printing and Copying.....	53
2.5.1 Polymer 3D Printing Process—FDM.....	53
2.5.2 Polymer 3D Copying Process—Injection Molding.....	56
References	80
3 Polymeric 3D Printers	83
3.1 Common Techniques for Polymer 3D Printing.....	84
3.2 Polymer Direct Melt 3D Printing Equipment.....	93
3.2.1 Free-Forming Machines	94
3.2.2 Melt Differential 3D Printers.....	94
3.2.3 Theoretical Analysis of Melt Differential 3D Printing...	98

3.2.4	Design of the Melt Differential 3D Printing Device.....	122
3.2.5	Industrial-Grade Melt Differential 3D Printer.....	130
References		134
4	Polymeric 3D Copiers	137
4.1	Overview	137
4.2	Components and Classification of 3D Copiers.....	138
4.2.1	Components of a 3D Copier.....	138
4.2.2	Classification of 3D Copiers.....	143
4.3	How 3D Copiers Work.....	149
4.3.1	Plasticization	150
4.3.2	Mold Filling and Forming.....	157
4.4	Basic Parameters of 3D Copiers.....	160
4.4.1	Main Parameters of the Injection Unit [7].....	160
4.4.2	Main Parameters of the Clamping Unit [8].....	163
4.5	Structural Design of 3D Copier.....	164
4.5.1	Injection Device	164
4.5.2	Clamping Device	175
4.5.3	Drives and Safety Devices.....	183
4.6	Process Control of 3D Copier [12].....	186
4.6.1	Core Principles of Product Accuracy Control.....	186
4.6.2	Process Control Methods for Product Accuracy.....	188
4.7	Precision 3D Copier.....	190
References		202
5	Materials and Defect Analysis for Polymer 3D Copying.....	205
5.1	3D Copying Materials.....	205
5.1.1	Classification of 3D Copying Materials.....	205
5.1.2	Melt Characteristics of Materials.....	214
5.1.3	Processing Properties of Materials.....	223
5.1.4	Microscopic Properties of Materials.....	240
5.2	Visualization of the Mold Cavity.....	247
5.3	3D Copying Defect Generation Mechanisms and Solutions.....	251
5.3.1	Common Defects in Manufactured Products.....	252
5.3.2	Generation Mechanisms of Typical Defect [30, 31].....	253
5.3.3	Causes and Solutions of Defects in 3D Copied Products	257
References		283
6	The Future of Polymer 3D Copying Technology.....	285
6.1	Smart Manufacturing of Molds	285
6.1.1	3D Printing of Molds	286
6.1.2	Adaptive Molds.....	295

6.2 3D Pressing Technology.....	298
6.3 The Age of Smart IoT.....	302
References	305
Index	307

Chapter 1

Introduction



With the continuous development of society, the application proportion of polymers in various fields is increasing year by year. It even shows better performance than metal materials, not only can meet the strength and rigidity requirements of metal materials, but also can be flame-retardant, conductive, and anti-oxidation by adding additives to meet the requirements of specific occasions. In some areas, it has replaced metal materials such as steel. And the polymer processing and advanced manufacturing technology have also made great progress. It is developing in the direction of being more precise, more energy-saving and more efficient.

Polymer 3D printing technology is an advanced manufacturing technology, which provides a new manufacturing method for materials to structures. It is a “from scratch” additive manufacturing method, which breaks through the technical bottleneck of traditional manufacturing technology in the manufacture of complex shape products. It can also quickly produce complex shapes and structural features that are difficult or even impossible to process with traditional technology. However, due to the high cost of its equipment and materials, as well as the low precision and strength of its products, the scope of application is greatly restricted. Besides, since “3D printing” constructs products in layer-by-layer stacking, its molding efficiency is relatively low.

The polymer “3D copy technology” developed based on polymer molding technology is a “from one to many” method of equal material manufacturing. It accurately replicates three-dimensional entities, then injects molten polymer into a specific cavity for cooling and solidification. Polymer “3D copying” technology uses injection molding equipment as a “3D copying machine”, using 3D printing molds to realize three-dimensional copying of plastic products with complex structural characteristics. The production process is highly automated, efficient, fast, and high precision products. The “3D copier” is the same as the traditional paper copier, which can realize fast, high-precision, and numerous copying of samples. The value of copying lies in “low cost and high efficiency”, so 3D copying technology has broad application prospects and can meet increasingly urgent market demands. The

3D copying process is roughly divided into three stages: product physical scanning or prototype construction, mold design and printing, molding. Whether it is high-precision product manufacturing or mass production, “3D copying” technology has unparalleled advantages over other technologies.

1.1 Introduction to 3D Printing

With the simultaneous advancement of new industrialization, informatization, and urbanization, the potential of residents’ consumption continues to be released, customer needs are becoming increasingly diversified and personalized, product updates are accelerating, production cycles are shortening, quality requirements are getting higher and higher, and costs are increasing lower. The multi-variety, small-batch production mode has become a mode of the modern economy of enterprises [1–3]. The rapid development of the demand for personalized, small-batch polymer medical products, aerospace accessories, and cultural products has continuously expanded the demand for R&D and design sample manufacturing. Therefore, a plastic molding method that meets the rapid processing of small batches has become a research hotspot.

3D printing technology is an important research field in advanced manufacturing technology. Its advantage lies in the preparation of complex curved products, near-net shaping, digital design, and manufacturing, etc. [4]. After more than 30 years of development, 3D printing technology has rapidly shifted from concept, process, and equipment research to industry applications, which has brought a profound impact on the development trend of traditional manufacturing and smart manufacturing. According to the type and method of processing materials, it can be classified into metal 3D printing, polymer 3D printing, and biological material 3D printing.

The ordinary printing that we usually use is to print the flat objects output by the computer. But in fact, the working principle of 3D printing is basically like that of ordinary printing. Different from ordinary printing, 3D printing uses metal, plastic, and other materials to stack digital three-dimensional models into three-dimensional entities.

Compared with traditional processing methods, the production cost of 3D printing technology has nothing to do with the complexity of the product, only the amount of materials used and the cost of materials. Therefore, the manufacturing cost can be reduced. 3D printing technology can directly print the entire part without assembly, and greatly expand the range of processed product shapes. Because of these advantages, 3D printing will gradually penetrate people’s lives in the future and be more widely used.

1.1.1 How 3D Printing Works

3D printing is also known as additive manufacturing and rapid prototyping. ASTM International Committee F42 on Additive Manufacturing Technologies defines its principle as: “a process of joining materials to make objects from 3D model data, usually layer upon layer” [5]. The working principle of it is basically the same as that of ordinary printing. The printer contains liquid or powder as the “printing material”. After connecting to the computer, the “printing materials” are superimposed little by little through computer control, and finally the blueprint on the computer becomes a real object.

The prerequisites for 3D printing are 3D printing materials, 3D printers and designed 3D model. 3D printing materials are just like the “A4 paper” and “ink” of ordinary inkjet printers. If you want to print different types of models, you only need to select the corresponding 3D printing materials according to your own needs and the actual situation to print the final work. One thing to mention is that if you choose metal materials, you need to choose the corresponding metal 3D printer.

The basic processing flow of 3D printing can be divided into 5 steps, as shown in Fig. 1.1.

- ① 3D modeling Use 3D software to build 3D surface or solid model. Available software includes engineering software such as NX, Pro/E, SolidWorks, and complex surface modeling software such as Rhinos, Maya, 3Dmax.
- ② Stereolithography(STL) STL file is a kind of digital mesh file, which can describe the geometric information of three-dimensional objects. You can first set the chord height in the 3D software to improve the accuracy of the model, and then export the digital file of the model.
- ③ Models slicing Import the STL file into the 3D printing software for model slicing and process setting. Different types of 3D printers have different process setting software. For example, open-source 3D desktop printer process setting software such as Cura, Simplify, and Makerware. For industrial-grade 3D printers, the software and equipment are combined, so there is less open-source software. In the software, set the printing speed, filling rate, temperature, pressure, and other parameters. Then slice the digital model and plan its path.

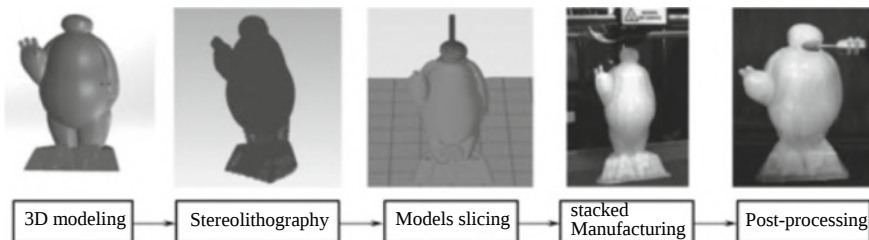


Fig. 1.1 Basic 3D printing process

Finally, a sentence that can be recognized by a 3D printer is formed, such as a Gcode slice file.

- ④ **Stacked manufacturing** Different types of 3D printers have different printing preparation processes, which are related to consumables and processes. But they are all processed in a layer-by-layer stacking method. In this way, the complex physical entities are converted into two-dimensional lamellar processing, which avoids the influence of the complexity of the product structure on the processing technology and reduces the processing difficulty.
- ⑤ **Post-processing** After the printing is completed, in order to ensure the surface accuracy and other properties of the product, a series of post-processing is required, such as removing the support structure, cleaning the residual powder and resin, etc. Surface smoothing treatment can also be carried out in acetone vapor. And in order to improve the mechanical properties of the product, post-treatment methods such as ultraviolet radiation are used.

1.1.2 History of 3D Printing

The idea of 3D printing originated from a patent for layered structure topographic maps in the United States at the end of the nineteenth century. In 1984, Hull proposed the concept of rapid prototyping, but the real establishment was marked by the declaration of three-dimensional printing patents in 1991 by Scans E.M and Cima M.J of the Massachusetts Institute of Technology. In the past thirty years, 3D printing technology has developed rapidly. Its development process is shown in Fig. 1.2. In 2005, Zcrop successfully developed the first high-definition color 3D printer—Spectrum Z510. In November 2010, the American Jim Kor team created the first 3D printed car-Urbee. After that, there even appeared 3D printed metal guns/aircrafts, etc.

The 3D printing process is mainly divided into the following 7 categories [6]: material extrusion, material jetting, binder jetting, sheet lamination, vat photopolymerization, powder bed fusion, and direction energy deposition. Each category contains many categories, and the molding process is slightly different.

The 3D printing processes that are commonly used in polymers and have been widely used are as follows: fused deposition modeling (FDM), selective laser sintering (SLS), stereo lithography apparatus (SLA), laminated objected manufacturing (LOM), three-dimension printing (3DP), and micro-droplet jetting (MDJ). These 6 printing processes have their own advantages and disadvantages. Different molding processes can be selected according to the different consumables or the price of the 3D printing equipment, which will be described in detail in the subsequent chapters.

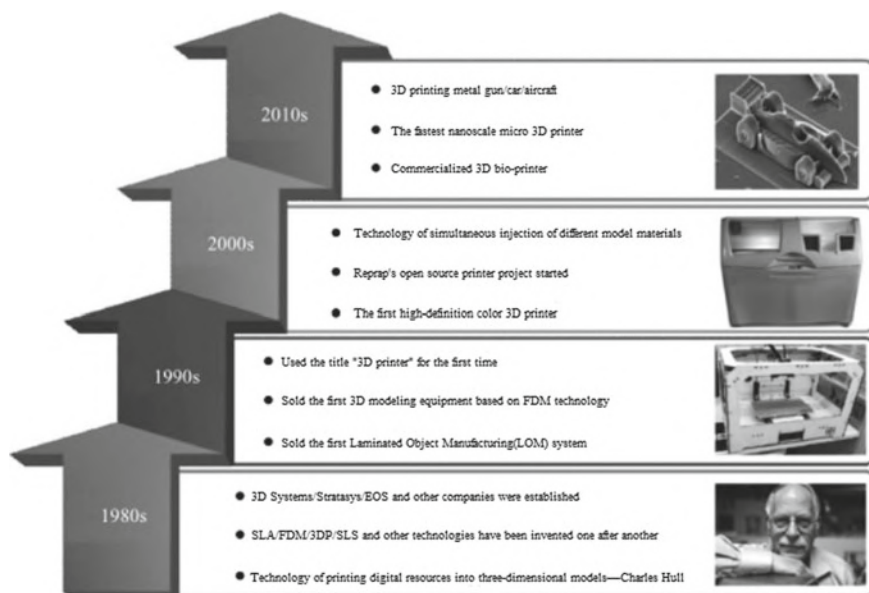


Fig. 1.2 The development of 3D printing

1.1.3 Application of 3D Printing in Polymer Processing and Molding

According to Wohlers 2015 research report [6], the application of 3D printing technology is becoming more and more extensive. In 2014, 13,393 non-metal printers were sold, of which equipment used for polymer processing accounted for more than 90%. Polymer-based 3D printing products are mainly used in model products and structural functional products, mainly distributed in: ① visual teaching aids, used in engineering, design and medical teaching; ② display model, applied to the field of architecture and innovative design display; ③ structural devices, used in the field of mechanical structures for temporary assembly; ④ casting molds, used in small batch reversal molds or casting male molds; ⑤ functional products, used in related product fields with special purposes.

Researchers have made a lot of attempts in the application field of polymer 3D printing products, and optimized the 3D printing process for their special applications, broadening the application range of 3D printing.

1.2 Introduction to 3D Copying

3D copying is a concept put forward compared to 3D printing technology. As the name suggests, it refers to the technology of mass copying three-dimensional entities. In a narrow sense, that is, polymer molding technology, including injection molding, blow molding, rotational molding and so on. Broadly speaking, all technologies that rely on “molds” to reshape products fall into the category of 3D copying, such as metal casting, metal die casting, and metal stamping.

The 3D copying process is divided into three stages: product entity scanning or prototype construction, mold design and manufacturing, molding. Product entity scanning refers to the acquisition of three-dimensional data of the entity based on materialization, and then import it into the computer system. Product prototype construction refers to the use of 3D drawing software and simulation software to design and optimize products based on digitization, and then form 3D data.

Mold is the core component of 3D copying. Its function is to control and restrict the flow of materials (solid or liquid) to form the required shape. Mold is widely used in manufacturing because of its high efficiency, good product quality, low material consumption, and low production cost. In electronics, automobiles, motors, electrical appliances, meters, home appliances, and communication products, 60–80% of parts are formed by molds. The quality of the mold determines the quality of the product. Therefore, the mold is called the “mother of industry”. The mold is also a “benefit amplifier”. The value of the final product produced by the mold is often dozens of times, or even hundreds of times, of the value of the mold itself.

The traditional mold manufacturing is mainly through machining, and the molding cycle is long. In the 3D copying process, the molding cycle can be shortened by 3D printing molds or mold cores. 3D printing molds are mainly divided into plastic molds and metal molds. First print the plastic mold for trial and repair, and then print the metal mold to form and copy the final product.

Since the beginning of the twentieth century, with the rapid development of manufacturing and economic levels, molding has become one of the most important processing methods in the manufacturing industry due to its advantages of high molding efficiency and good product quality (Fig. 1.3). The level of craftsmanship and technological content of mold processing has become an important indicator of a country’s technological and product manufacturing level. To a large extent, it determines the product quality, efficiency, new product development capabilities, and determines the international competitiveness of a country’s manufacturing industry.

1.2.1 How 3D Copying Works

The basic principle of 3D copying (Fig. 1.4) is to make a mold cavity based on the structural contour and shape characteristics of the three-dimensional entity. Then the material is injected into the mold cavity, and under the action of external force or the



Fig. 1.3 3D copying technology

phase change of the material itself, it is copied and formed. During this processing, different materials need to be controlled separately to reach the required processing temperature. Then according to the pre-set process, the material is injected into the mold, and finally cooled and solidified to obtain the desired product.

There are many basic methods for 3D copy molding. Two methods are mainly introduced here: one is injection molding technology and its derivative technology; the other is rotational molding technology.

(1) Injection molding technology and its derivative technology.

Injection molding technology (abbreviated as injection molding technology) is a technology that injects molten polymer material into a mold cavity, and then cools and solidifies to obtain a molded product. It is one of the most important process

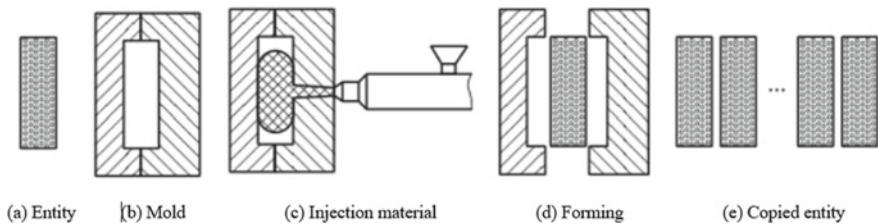


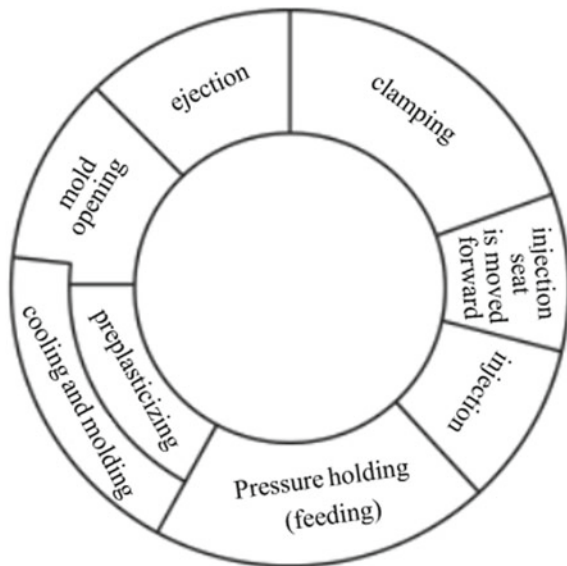
Fig. 1.4 Working principle of the 3D copying

methods for plastic products processing and molding, and it is also one of the most basic and most widely used forms of 3D copy technology [7].

Injection molding is a cyclically reciprocating process. From the perspective of the unit operation of the injection molding machine (injection molding machine for short), its actions are divided into the stages of plasticization, injection, mold filling, pressure holding, cooling, and demolding. The working process cycle is shown in Fig. 1.5. The cycle starts when the mold is closed, and then the melt is injected into the cavity; after the cavity is full, the pressure will continue to be maintained to supplement the shrinkage of the material, which is called pressure holding; at the beginning of the material cooling process, the screw starts to rotate, and the material is stored at the front end of the screw for the next injection; after the product is sufficiently cooled, the mold is opened and the product is ejected. The time to complete a cycle is called the molding cycle, which is an important indicator of productivity and equipment utilization.

- ① Mold closing and locking the copying process of the injection molding machine starts from the closing of the mold. The movable template first moves to the fixed template at a high speed. When the two are about to touch, the movable template is reduced to a low speed to compress the fixed template. After the pressure between the dynamic and fixed templates reaches the required value, the signal is fed back to the control system. Then proceed to the next action.
- ② Move the injection seat forward, inject and maintain pressure After receiving the signal from the control system, the injection system starts to move slowly to the mold system until it overlaps with the mold. The screw is moved forward quickly under the drive of the injection cylinder, and the melt is injected into the

Fig. 1.5 Working process cycle of injection molding machine



mold at a certain pressure and speed. However, due to the cooling effect of the low temperature mold, the melt injected into the mold will shrink over time. In order to compensate for this part of the shrinkage and produce dense products, usually there is a small amount of melt (material cushion) at the front end of the screw. During the shrinking process, this part of the melt enters the mold. At this time, the screw will correspondingly move forward for a short period.

- ③ Product cooling and pre-plasticization The melt begins to cool when it enters the mold. After the cooling reaches a certain level, the gate is closed. At this time, the melt cannot flow back to the injection system, and the product is slowly cooled and shaped in the mold. In order to shorten the molding cycle and improve production efficiency, while the product is cooling, the injection system begins to prepare for the next injection. The screw rotates, and the pellets or powder in the hopper are transported forward for melting and plasticization. Under normal circumstances, the forward pressure of the melt is lower than the resistance given to it by the nozzle, but greater than the return resistance of the working oil of the injection cylinder, so the screw retreats while rotating, and the amount of back movement is the amount of the material cushion. When the screw retreats to the measured value, the screw stops rotating.
- ④ Move back the injection seat and remove the product After the screw is plasticized and metered, the injection system moves back and the mold opens. The finalized product is ejected by the ejector mechanism, and an injection molding cycle ends.

In the entire molding cycle, injection time and cooling time are the most important, which have a decisive influence on the quality of product molding. Injection time includes two parts: filling time and holding pressure time. The filling time is relatively short, generally 3~5 s; the holding pressure time takes up a larger proportion, generally 20~120 s (it is longer when the wall thickness increases). The filling process of the injection molding machine is completed in the speed control mode. After the speed/pressure switching point, it is converted to the pressure control mode to start the pressure maintaining. The determination of the speed/pressure switching time directly affects the product quality.

In the process of holding pressure, the relationship between holding pressure and time is called holding curve. If the holding pressure is too high or the holding time is too long, the product is prone to flash and the residual stress is high. And the holding pressure is too low or the holding time is too short, the product is easy to produce shrinkage marks, affecting the quality of the product. Therefore, there is an optimal value of the pressure holding curve. Before the gate solidification, the pressure curve with the smallest fluctuation range of product shrinkage rate is usually taken as the criterion.

The cooling time mainly depends on the thickness of the product, the thermal and crystalline properties of the plastic, as well as the temperature of the mold. If the cooling time is too long, it will affect the molding cycle and reduce productivity. If the cooling time is too short, the product will stick to the mold and be difficult to demold, and the finished product will be demolded before it is completely cooled and solidified, which is easy to be deformed by external forces. The other time in the



Fig. 1.6 Multi microinjection molding technology

molding cycle is related to the performance and automation of the injection molding machine [8].

Injection molding technology is developed based on the principle of metal die-casting. With the continuous advancement of science and technology, the injection molding process continues to innovate, such as injection compression molding, plastic injection stretch blow molding, gas-assisted injection molding, transfer molding (RTM technology), reaction injection molding, microcellular foaming injection molding, multi-component injection molding, multi microinjection molding [9] (Fig. 1.6), nano injection molding and so on.

(2) Rotational molding technology

Rotational molding technology [10] is a special polymer product molding technology that conforms to the market demand for large plastic products. It is a process method for manufacturing hollow plastic products under high temperature and low-pressure conditions. It is suitable for molding large-size and super-size hollow products with fine surface textures and complex shapes. The processed products have the advantages of uniform wall thickness, stable size, no residual stress, no forming seams, no corner waste, etc.

The rotational molding process is mainly divided into four stages: filling, heating, cooling, and demolding (Fig. 1.7), as follows.

- ① **Filling** According to scientific calculations, the required thermoplastic engineering plastics will be weighed and pretreated, and injected into the cavity of the rotational molding mold in the form of powder or liquid.
- ② **Heating** Place the rotational molding equipment in the heating chamber to heat the rotational molding mold. While heating the rotational molding mold, the inner and outer shafts (also called main and auxiliary shafts) are rotated according to

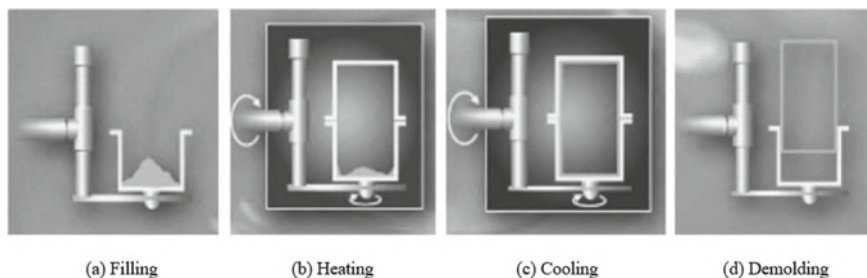


Fig. 1.7 Rotational molding process principle

a certain rotation speed ratio, so that all the powder is adhered and solidified on the inner surface of the rotational molding mold cavity.

- ③ **Cooling** The rotational molding mold is moved from the heating chamber to the cooling chamber, so that the thermoplastic powder in the rotational molding mold cavity is cooled to a temperature that can be shaped. In this process, precise cooling time and cooling conditions need to be set according to the flow properties of the material, the structure and shape of the product, and the rotational molding device needs to keep rotating continuously.
- ④ **Demolding** By setting the rotational speed of the inner and outer shafts of the rotational molding device, the rotational molding device is located at the set mold opening position. Then open the rotational molding mold and take out the product. Finally, finalize the product (you can judge whether it needs to be finalized according to the complexity of the product structure).

Rotational molding is mainly used to manufacture large-scale plastic products, such as furniture, kayaks, and military packaging boxes. As shown in Fig. 1.8. The current rotational molding equipment, molds and process technology are still relatively backward compared with other plastic molding methods. In addition, this technology has the problems of long molding cycle and high energy consumption, which to a large extent restricts the wide application of rotational molding technology in the field of polymer molding.

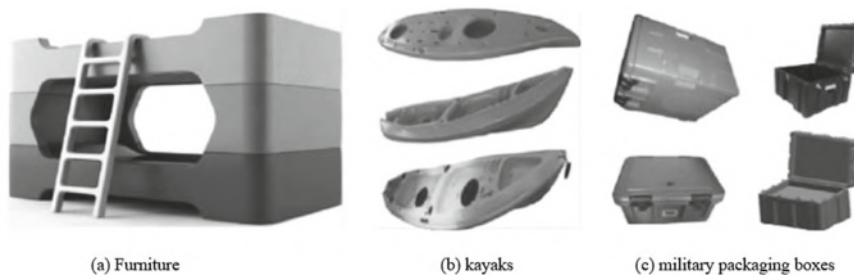


Fig. 1.8 Some typical rotational molding products

1.2.2 The Significance of 3D Copying

In the process of exploring the direction of the industry, the emergence of 3D printing has rapidly updated the industrial design of products and has a positive impact on the production process of modern manufacturing. However, 3D printing builds products in a layer-by-layer manner, which is difficult to process and relatively low in molding efficiency. Compared with 3D printing, 3D copying represented by injection molding has more urgent market demand and broad application prospects in the field of molding. 3D copying technology uses injection molding equipment as a 3D copier to realize three-dimensional copying of plastic products with complex structural characteristics. The production process is highly automated, with high efficiency, high speed, and high product precision. Whether it is high-precision product manufacturing or mass production, 3D copying technology has unparalleled advantages over other technologies.

Since the twentieth century, people's material life and spiritual life have had higher requirements. People's growing material and cultural needs inevitably depend on advanced social productivity, and high-volume, high-precision product manufacturing technology emerges at the historic moment. Therefore, the emergence of 3D copying technologies such as injection molding and rotational molding has made mass production of the same product possible. The biggest feature of 3D copying technology is its high molding efficiency. For example, at the 2013 German International Rubber and Plastics Exhibition (K2013), Arburg launched an ultra-high-speed injection molding machine that produces 64 thin-walled parts in 1.85 s. It is used for the manufacture of thin-walled flat dripper with fine metalwork structure for drip irrigation system. KraussMaffei demonstrated the high-speed injection bottle cap technology on site. The injection molding cycle is only 2.1 s. One equipment can produce more than one billion bottle caps a year, which greatly improves production efficiency (Fig. 1.9).

1.3 The Difference Between 3D Printing and 3D Copying

3D printing is the stacking of droplets in dots. It has great flexibility in forming complex products, but it has shortcomings such as long molding cycle, low molding efficiency, narrow range of raw materials, and product accuracy that cannot meet actual production needs. Therefore, 3D printing is mainly oriented to multi-variety, small-batch production. At present, conventional wire 3D printers have been widely promoted and applied. The printing materials mainly include PLA and ABS, which are mainly used for the molding of handicrafts and decorations. The application field of 3D printing is very extensible, but it is still in the conceptual or initial stage, such as 3D printing food, 3D printing house, 3D printing bones, 3D printing space parts, etc. As 3D printing technology matures, it is believed that these ideas will be maturely applied soon (Fig. 1.10).

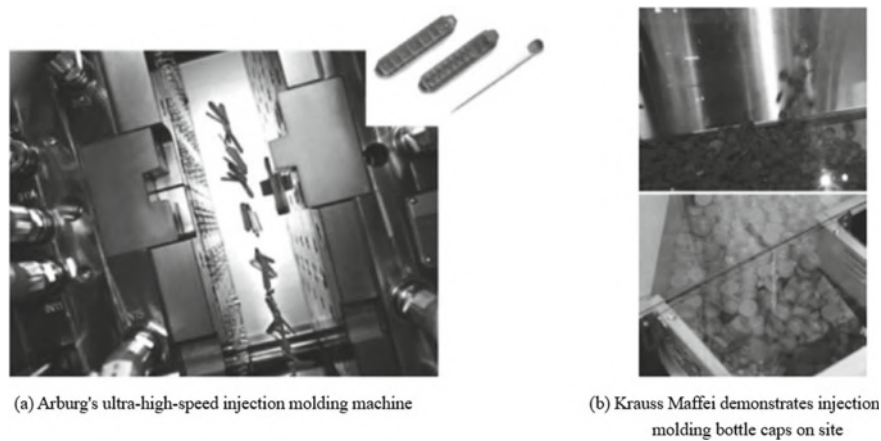


Fig. 1.9 Ultra-high-speed injection molding machine launched at K2013

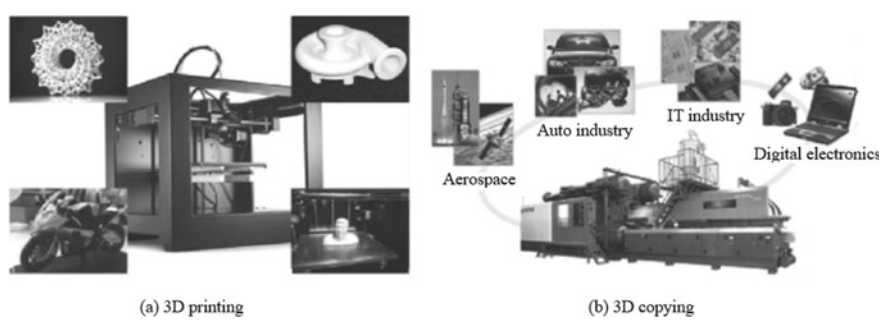


Fig. 1.10 Applications of 3D printing and 3D copying

3D copying uses the cavity as a unit for liquid filling, which is divided into forms such as one mold with one cavity, one mold with multiple cavities, and insert injection. It has the advantages of short molding cycle, high molding efficiency, wide range of raw materials, and high product accuracy. However, mold manufacturing costs are relatively high. It is mainly oriented to single product, mass production, and is widely used in the manufacturing fields of daily necessities, automobile industry, aerospace, medical equipment, electronic appliances, etc. (Fig. 1.10).

Before the birth of 3D printing technology, the processing and manufacturing industries all over the world used molds as the main production force. Molds have made great contributions to the processing and manufacturing industry, so they are also known as the “mother of industry”. The 3D printing process does not require molds, but is additively manufactured by stacking and forming, just like swallows make nests, which accumulate little by little with mud in their mouths. After a certain period of accumulation, the final product is formed.

The differences between 3D printing and traditional molds are as follows.

Traditional molds:

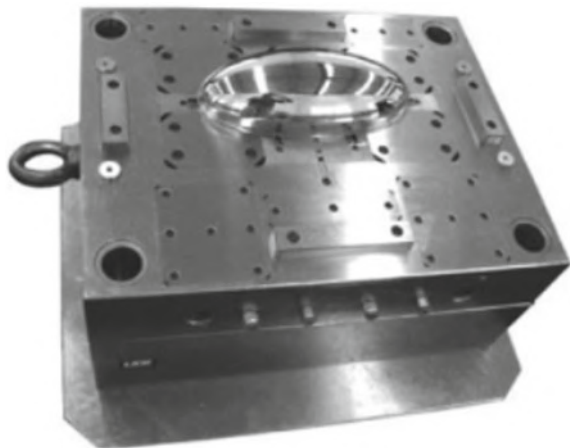
- ① Durability of the mold: It must be wear-resistant and economical. In view of this, most of the molds are made of steel, and some are even made of cemented carbide.
- ② Mold manufacturing: Use 3D modeling software, such as PRO/E to draw the mold diagram, and after continuous adjustment to achieve the final molding effect.
- ③ Purpose of the mold: Mainly based on traditional injection and stamping products.
- ④ Strength and accuracy of the mold: Confirm the strength according to the actual needs of users, and the molding accuracy is high.
- ⑤ Molding production cycle: The forming speed is relatively fast.

3D printing technology:

- ① Materials required for 3D printing: Consider the most suitable 3D printing materials according to the actual needs of users.
- ② 3D printing molding method: Accumulative type, increase little by little, and finally complete the printed work.
- ③ Purpose of 3D printing: Small and complex parts can be easily realized by 3D printing. Large parts, integral printing, and assembly.
- ④ Strength and accuracy of the 3D printing: There are many comprehensive factors regarding the strength and accuracy of 3D printing. The accuracy of the 3D printer, the quality of the selected materials, and the accuracy of the 3D model map all determine the accuracy and strength of the final product. The strength and accuracy of 3D printing are improving at a rapid pace.
- ⑤ Production time of 3D printing: The molding time is relatively long.

Figure 1.11 is a physical drawing of the mold.

Fig. 1.11 The physical picture of the mold



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Chapter 2

Polymer 3D Printing and 3D Copying Processes



Whether 3D printing technology or 3D copying technology, its technological process is similar to that of paper printing copier. It includes data acquisition, model analysis, raw material preparation, sample replication and other technological processes, as shown in Fig. 2.1.

2.1 Data Acquisition

Before 3D printing or 3D copying, it is necessary to obtain the information of the solid model, including its size, contour, structure information, etc. Therefore, to get the solid sample, users need to map and scan to the three-dimensional object.

For the data acquisition of three-dimensional entities, the traditional collection means is on-site surveying and mapping, including collecting the size, contour and other information of the entity, so as to get two-dimensional drawings. After then, 3D modeling or direct processing and manufacturing is available. The appearance of 3D scanner makes the data acquisition of 3D entities simpler and more convenient. The 3D scanner can measure the object at high speed and high density, and output the 3D point-cloud for further post-processing. The point cloud scanned by the 3D scanner can be converted into the format by the point cloud processing software and input into each 3D software users need. For example, Geomagic Studio is a special software for processing 3D point cloud. It can process the 3D point cloud data into various required formats, such as STL format. Then users can import it into 3D printing slicing software such as Cura and Simplify for model slicing and process parameter setting, or import it into 3D modeling software such as 3Dmax, CAD, Pro/E, UG, CATIA, Imageware, ZBrush to facilitate further processing.

The purpose of 3D scanners is to create point clouds of objects' geometric surfaces. These points can be used to interpolate the shape of the object's surface. The denser

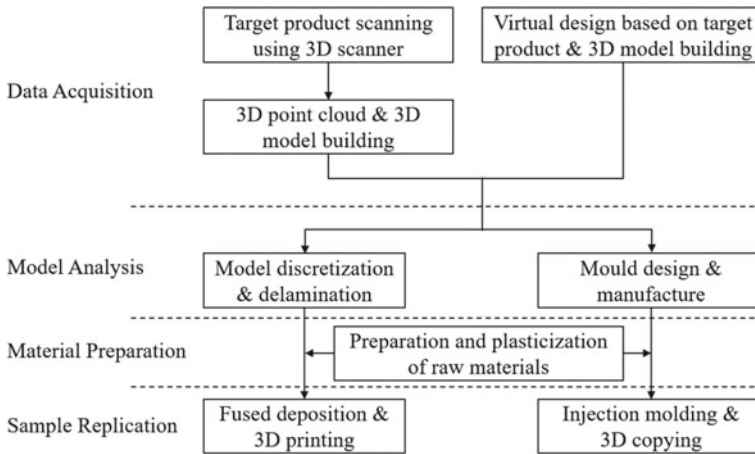


Fig. 2.1 3D printing and 3D photocopying process

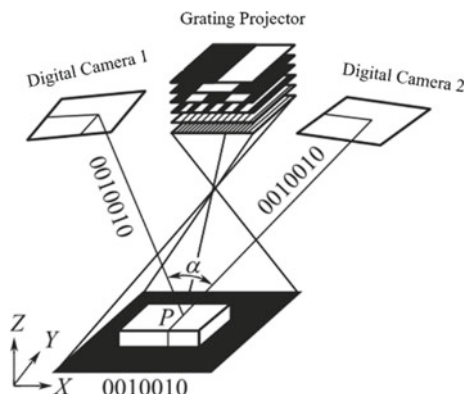
the pointcloud, the more accurately the model will be created (this process is called 3D reconstruction).

The earliest 3D scanners adopted contact measurement methods, such as 3D Coordinate Measuring Machine. Although the accuracy reached the micron level ($0.5\ \mu\text{m}$), its application field was limited due to its huge size, high cost and inability to measure soft objects. Therefore, the non-contact measurement method appears, mainly divided into two categories: one is passive. It completely depends on the natural light conditions instead of a specific light source to scan. It often uses the binocular technology, but its low accuracy make it only scan out the geometric features of the object. Therefore, it can't meet the requirements of many fields. The other is the active way, which is to project a specific light to the object. The representative technology is laser line scanning. Although it has high accuracy, only projecting a light each time leads to the slow scanning speed. In addition, lasers cannot be used in certain fields because they can cause damage to living organisms and more precious objects.

The emerging technology is non-contact scanning of structured light, which is an active method. By projecting multiple rays of light simultaneously through a projection or grating, one surface of an object can be captured. Only information of several surfaces is needed to complete the scanning. It is characterized by fast scanning speed and programmable realization.

Structured light non-contact scanning is a composite 3D non-contact measurement technology that combines structured light, phase measurement and computer vision. So, it is also called "3D structured light scanner". Its basic principle is shown in Fig. 2.2. When measuring, the grating projection measurement device projects several specific coding structured light to the object. Then the two cameras with a certain angle pick synchronous corresponding image, and finish the image decoding and phase calculation. Finally, users can get the two cameras public visual

Fig. 2.2 Principle of 3D structured light scanner



three-dimensional coordinates of pixels by using the matching technology, triangle measuring principle.

This measurement technique makes it possible to take photographic measurements of objects. The photogrammetry is similar to the camera taking pictures of the objects in the field of vision. The difference is that the camera takes the two-dimensional image of the object, while the three-dimensional scanner gets the three-dimensional information of the object. Unlike traditional 3D scanners, the scanner can measure one surface simultaneously.

The 3D scanner can be moved to the workpiece position at will for on-site measurement, and can be adjusted to any angle for omni-directional measurement. Using it, large workpiece can be measured in blocks, and measurement data can be combined automatically in real time. So, it is very suitable for various sizes and shapes of objects (such as car, motorcycle shell and interior decoration, home appliances, sculpture, etc.) measurement.

2.2 Data Processing

The data processing of three-dimensional entity mainly depends on various kinds of software. Data processing software includes 3D modeling software, numerical analysis software, point cloud processing software, 3D printing slicing software, etc.

2.2.1 Three-Dimensional Modeling Software

For 3D printing, in addition to scanning 3D entities through 3D scanner, 3D modeling software can also be used to directly model, so as to improve the accuracy of the model and facilitate the optimization of design. Because the 3D scanner is used for

entity scanning, the scanned entity may be incomplete and it is difficult to optimize the structure. In addition, the accuracy of the model is limited by the density of the point cloud.

For 3D photocopying, data analysis and modeling by means of computer-aided design (CAD) have become one of the necessary means for engineers to conduct mechanical design. Through the 3D modeling software, users can complete the optimization of the structure of the mold, time reduction of the test and repair, reduction of the test cost and improvement of the work efficiency. Besides, the model established by the 3D modeling software can be further imported into the finite element analysis software for computer-aided engineering design (CAE), such as structural mechanics analysis, mold flow analysis, etc.

Three-dimensional modeling software is mainly used to build three-dimensional solid models, and optimize the structure design. By using it, users can greatly save the design time and energy and the model has higher accuracy. Common three-dimensional modeling software includes Pro/E, SolidWorks, UG (Unigraphics), CATIA, etc.

(1) Pro/E

① Overview of Pro/E

Pro/E is the abbreviation of Pro/Engineer, which is a powerful three-dimensional design software with CAD/CAM/CAE integration. It is developed by PTC (Parametric Technology Corporation) company in the United States. Pro/Engineer is famous for its parameterization, and it is the earliest application of parameterization technology. Therefore, it occupies an important position in the field of 3D modeling software. To ensure that users have choices according to their own needs, Pro/E adopts modular mode and can be used for sketching, parts production, assembly design, sheet metal design, processing, etc.

② Application scope of Pro/E

Pro/E is widely used in the design and analysis of construction machinery. During the mechanical design, users can quickly have a visual understanding of the object to be processed, by using various functional modules of Pro/E. It can be used on workstations or on stand-alone machines.

③ Features of Pro/E [1]

- a. Parametric design. Pro/E is the first CAD software to put forward the concept of parametric design. The so-called parameterization design is relative to the product. When the product is regarded as geometric model, it can break down to a feature structure by finite energy treated, and each feature structure can be decomposed and quantified.
- b. Feature modeling. Feature modeling is to decompose a very complex geometric model and then parameterizes its finite feature structure. Pro/E is a feature-based entity modeling system. Engineers use intelligent feature-based functions to generate models like cavities, shells, chamfers and fillets, and they can sketch

and easily change models. This feature provides engineers with unprecedented simplicity and flexibility in design.

- c. Single database processing. Single database processing workflow of Pro/E is that each piece of data works independently for the product, all from the same database. In other words, changes in any part of the whole design process can also be reflected in the relevant links of the process before and after the whole design. For example, The NC (numerical control) tool path is automatically updated as soon as the engineering detail is changed. Any changes to the assembly drawings are fully reflected in the entire 3D model. The complete integration of this unique data structure and engineering design results in better design, higher finished product quality, better product delivery to market, and lower price.

(2) SolidWorks

① Overview of SolidWorks

SolidWorks is a set of CAD/CAE/CAM/PDM desktop integrated system based on Windows. It is the first mechanical CAD software under the Windows implemented by SolidWorks Company of America on the basis of the large-scale mechanical CAD. It was successfully developed in January 1995. It is very convenient to realize complex 3D parts solid modeling, complex assembly and generating engineering drawings. It mainly includes mechanical parts design, assembly design, animation and rendering, advanced finite element analysis technology and sheet metal production modules. It has powerful functions, and fully meets the needs of mechanical design [2]. Besides, it can provide different design solutions, reduce errors in the design and improve product quality.

② Application scope of SolidWorks

At present, choosing SolidWorks has become a leading and mainstream 3D CAD solution. The software can be used in the design and production preparation of mechanical products with regular geometry.

③ Features of SolidWorks [3]

- a. Modeling based on feature and parameterization. A SolidWorks assembly consists of parts, which consist of features (for example, bosses, threaded holes, stiffened plates, etc.). This feature modeling method directly displays familiar 3D objects and reflects the designer's intention.
- b. Skillfully solved multiple correlations. The creative process of SolidWorks consists of three-dimensional and two-dimensional alternating processes. Therefore, the complete design document includes the parts file, the assembly file and the engineering drawing file of both. Solidworks successfully handles the multiple connections that exist in the creative process, making the design process smooth, simple and accurate.
- c. Easy to learn and easy to use. SolidWorks software enables users to design, manufacture, and communicate. People familiar with the Windows system can

basically use SolidWorks for design. Its software icon is simple and clear. It has detailed help files and rich tutorials, and its core is sinicized to learn and understand easily.

(3) UG (Unigraphics)

① Overview of UG

UG (Unigraphics NX) is a product engineering solution produced by Siemens PLM Software company. It provides the digital modeling and verification means for users' product design and processing process. UG is a CAD/CAE/CAM integration of mechanical engineering computer software. It has high performance solid modeling ability, extremely convenient graphic display and editing ability. It provides a variety of modeling methods including feature modeling, surface modeling and solid modeling. It also provides top-down and bottom-up assembly design methods. And it provides powerful rendering, material, texture, animation, background, visual parameter setting and other support for outputting product design rendering.

② Application scope of UG

UG was first used in the United States McDonnell Douglas Aircraft Company. Its processing and manufacturing module function is extremely strong. And it has more than ten years' experience of successful application in the aviation and mold manufacturing industry, which is incomparable to other application software.

③ Characteristics of UG drawing module [4]

- a. In view display, users can flexibly choose the number no more than 6 and type of views according to the need. In addition to the common plane view, it also contains axonometric map, therefore, it's visual and intuitive. Besides, the advantage of UG in modeling drawing is that it only works on one view (point, line, etc.), and other views will automatically generate the corresponding projection geometry. It can also get the modeling user requires through some modules. This method is time-saving and accurate.
- b. UG can complete 3D composition through special curved surface and curve module with rotation and transformation of working coordinate system. The 2D drawing section can transfer the 3D solid model directly to the 2D different views. It can directly rotate, cut and step-cut the entity to produce section, which enhances the practicability of engineering drawing.
- c. With a good secondary development tool GRIP, users can add some programs to supplement the deficiencies of menu operation. It is a high-level FORTRAN-like language with statements to operate on various UG modules. Users can use GRIP language to establish and develop geometric graphics, use program control methods to perform some complex or repeated operations, and transform the interactive operations into batch processing.
- d. Auxiliary functions in modeling, such as dimensioning, are also very simple. It modifies the corresponding selection slightly through the storage of the system

itself, assisted by mouse operation. Various dimensions can be automatically generated. The format of the dimensions can be corrected and transformed according to the needs of users to ensure that they meet the standards. In addition, more complex geometric tolerance can also be marked.

④ Characteristics of UG manufacturing module

- a. The module has the NC machining capacity of 2.5~5 axes, which can directly process any entity model generated by the entity modeling module.
- b. It can automatically detect tool collision, avoid overcutting, and carry out the dynamic simulation of machining process and machining path simulation check. It can also give the machining direction, and consider the generation of the best tool path. As long as given the height of the tool mark, machining curved surface smooth can automatically determine the tool path and size.
- c. With a strong generality of post-processing program, it can generate G code programs of more than 80 kinds of CNC machine control systems such as Siemens, Fanuc, Cincinnati etc. CAD/CAM integrated manufacturing can be realized when the machine tool is driven.

(4) CATIA

① Overview of CATIA

CATIA is the flagship product development solution of Dassault, France. As a CAD software, it has powerful curve and surface modeling function, and it provide API [5] by using Automation technology. As an important component of PLM collaborative solutions, it can help manufacturers design their future products and support the entire industrial design process from the pre-project phase, detailed design, analysis, simulation, assembly and maintenance. As a fully integrated software system, CATIA organically combines mechanical design, engineering analysis and simulation, CNC machining and CATWEB network application solutions to provide users with a rigorous paperless working environment.

② Application scope of CATIA

CATIA is widely used in aerospace, automotive manufacturing, shipbuilding, machinery manufacturing, electronics and consumer goods industries, and its integrated solutions cover all product design and manufacturing fields. CATIA provides convenient solutions that cater to the needs of large, medium and small businesses in all industrial sectors. CATIA originated from the aerospace industry, but its powerful functions have been recognized by various industries. The famous users of CATIA include a large number of well-known enterprises such as Boeing, BMW, Benz, etc. Its user group plays a pivotal role in the world's manufacturing industry. Boeing

used CATIA to complete the electronic assembly of the entire Boeing 777, thus establishing CATIA as a leader in the CAD/CAE/CAM industry.

③ Features of CATIA

- a. CATIA has advanced hybrid modeling technology, including design object hybrid modeling, variable and parameterized hybrid modeling, and geometric and intelligent engineering hybrid modeling. CATIA has the ability to modify easily throughout the entire product cycle, whether for solid modeling or surface modeling, especially in the late stages. Because of the intelligent tree structure provided by CATIA, users can easily and quickly modify the product repeatedly. It is very easy for CATIA to make significant change at the last stage of the design, or to upgrade the original scheme.
- b. All modules of CATIA are fully correlated. Each module of CATIA is based on a unified data platform, so each module of CATIA has real full correlation. The modification of three-dimensional model can be fully reflected in the program of two-dimensional, finite element analysis, mold and numerical control machining.
- c. The design environment of concurrent engineering greatly shortens the design cycle. The multi-model linked working environment and hybrid modeling provided by CATIA make concurrent engineering design pattern no longer a fresh concept. As long as the general design department sends out the basic structure dimensions, the staff of each subsystem can start to work, which can work together without being involved with each other. Due to the interconnection between the models, the upstream design results can be used as the downstream reference, and the upstream design modification can directly affect the downstream work refresh, so as to realize the real concurrent engineering design environment.
- d. CATIA covers the entire process of product development. CATIA provides complete design capabilities: from the conceptual design of the product to the formation of the final product, it provides a complete 2D, 3D, parametric hybrid modeling and data management tools with its accurate and reliable solutions, to realize the process from the design of a single part to the establishment of the final electronic prototype.

2.2.2 Numerical Analysis Software

(1) Finite element analysis

Finite element analysis is a modern calculation method developed rapidly for structural mechanics analysis. It is an effective numerical analysis method which was first applied in the field of continuous mechanics—the analysis of static and dynamic characteristics of aircraft structure in the 1950s, and then it was widely used to solve continuity problems such as heat conduction, electromagnetic field and fluid

mechanics. At present, the most popular finite element analysis software includes ABAQUS, ANSYS and so on.

① ABAQUS

a. Overview of ABAQUS

ABAQUS is a powerful finite element software for engineering simulation, including a rich library of elements that can simulate any geometry, and a library of various types of material models that can simulate the properties of typical engineering materials. ABAQUS has two main solver modules, ABAQUS/Standard and ABAQUS/Explicit. It also includes a fully solver enabled graphical user interface, the human-computer interaction pre and post processing module ABAQUS/CAE. ABAQUS also provides specialized modules to solve specific problems.

b. Application scope of ABAQUS

Ranging of ABAQUS solving problems is from relatively simple linear analysis to many complex nonlinear problems. As a general simulation tool, ABAQUS can not only solve a large number of structural (stress/displacement) problems, but also simulate many problems in other engineering areas, such as heat conduction, mass diffusion, thermoelectric coupling analysis, acoustic analysis, etc. Because of its good pre-and post-processing program and powerful nonlinear solver, it has been increasingly widely used in seismic analysis of high-rise, long-span building structures and large bridge structures [6].

c. Features of ABAQUS

ABAQUS is widely recognized as the most powerful finite element software for analyzing complex solid and structural mechanical systems, especially for handling very large and complex problems and simulating highly nonlinear problems.

ABAQUS can not only analyze the mechanics of a single part and multiple physical fields, but also analyze and study at the system level. The system-level analysis features of ABAQUS are unique to other analysis software.

With its excellent analytical capability and reliability in simulating complex systems, ABAQUS has played a huge role in the research of a large number of high-tech products.

② ANSYS [7]

a. Overview of ANSYS

ANSYS is a large general finite element analysis software developed by ANSYS Company in the United States. It integrates structure, fluid, electric field, magnetic field and sound field analysis into one, and can interface with most CAD software to realize data sharing and exchange. ANSYS is an extensive suite of commercial engineering analysis software. The so-called engineering analysis software is that, it can know the mechanical structure system by the external force load after the state, and then judge whether to meet the design requirements, according to the mechanical

structure system by the external force load reaction, such as stress, displacement, temperature, etc.

b. Application scope of ANSYS

ANSYS software is widely used in engineering, and can achieve a certain degree of credibility in the fields of machinery, electrical machinery, civil engineering, electronics and aviation, etc. It has won praise from all walks of life.

c. Features of ANSYS

- Data unification. ANSYS uses a unified database to store model data and solution results, so as to realize the data unification of pre—and post-processing, analysis and solution and multi-field analysis.
- Strong modeling capabilities. ANSYS has the capability of 3D modeling, and all kinds of complex geometric models can be built only by GUI (graphical user interface) of ANSYS.
- Powerful solution function. ANSYS provides several solvers, and users can select the appropriate solver according to their analysis requirements.
- Powerful non-linear analysis function. ANSYS has powerful nonlinear analysis function, which can be used for geometric nonlinear, material nonlinear and state nonlinear analysis.
- Smart grid partitioning. ANSYS has intelligent meshing function, which automatically generates finite element meshing according to the characteristics of the model.
- Good optimization features.
- Good user development environment.

(2) Mold flow analysis

Mold flow analysis software is a simulation software for melt filling process, which can accurately predict melt filling, holding pressure, cooling, stress distribution, molecular and fiber orientation distribution, shrinkage and warping deformation of the product. So, it's convenient for the designer to find the problem as early as possible and make changes in time, rather than wait until after the mold test and then repair the mold. This is not only a breakthrough to the traditional mold design method, but also has great technical and economic significance in reducing or even avoiding the scrap of mold repair, improving the quality of products and reducing costs. The commonly used mold flow analysis software is Moldflow, Moldex3D etc.

① Moldflow

a. Overview of Moldflow

Moldflow is a powerful professional injection molding CAE software developed by Moldflow company in the United States. This software has an integrated user interface, which can easily input CAD model, select and find materials, establish model and carry out a series of analysis. At the same time, advanced post-processing

technology can bring convenience for users to observe and analyze the results, and it can also generate Internet-based analysis reports to conveniently realize data sharing [8].

Software Moldflow mainly includes the following two parts [9].

- Moldflow Plastics Advisers (MPA): After the design of the product, applying MPA to simulate and analyze, users can get the optimized product design scheme, and confirm the product surface quality in a very short time.
- Moldflow Plastics Insight (MPI): A software package for in-depth analysis of plastic products and molds. It can simulate and analyze the whole process of injection molding on the computer, including filling, holding pressure, cooling, warping, fiber orientation, structural stress and shrinkage, as well as gas-assisted molding analysis. Therefore, the designer can find out the possible defects of future products in the design stage, and improve the success rate of a mold test.
- Application scope of Moldflow

In its early years, Moldflow was mainly used in structural strength calculations and in the aerospace industry. At present, Moldflow software is widely used in the injection molding field of Moldflow analysis.

c. Features of Moldflow

Moldflow can be used to optimize the plastic products, to get the actual minimum wall thickness of the products and optimize the structure of the products. It can also optimize the mold structure to obtain the best gate location, reasonable flow channel and cooling system. What's more, it is able to optimize injection molding process parameters, to determine the best injection pressure, holding pressure, clamping force, mold temperature, melt temperature, injection time, holding time and cooling time, in order to inject out the best plastic products.

② Moldex3D

a. Overview of Moldex3D

Moldex is the abbreviation of MoldExpert. and Moldex is a three-dimensional solid model flow analysis software developed by KeSheng technology company. The software has the ability to calculate quickly and accurately. With the super humanized operation interface and the latest introduction of three-dimensional drawing technology, it can actually present all the analysis results, so that users learn more easily, and operate more conveniently.

b. Application scope of Moldex3D

The software can be used to simulate the process of filling, pressure holding, cooling and warping of molded parts in the molding process, and can accurately predict

the distribution of variables such as plastic melt flow state, temperature, shear stress, volume shrinkage and so on at the end of each process before the actual mold opening.

c. Features of Moldex3D [10]

Moldex3D features advanced numerical analysis algorithms, a user-friendly interface, a rich library of plastic materials, and a high-resolution 3D graphics display. Details are as follows.

- Moldex3D pioneered the true three-dimensional mode flow analysis technology. After rigorous theoretical derivation and repeated practical verification, many practical factors such as inertia effect, gravity effect and fountain effect are taken into consideration in the analysis. And it is accurate, stable and fast in calculation. With the aid of it, real 3D solid model flow analysis can be carried out, which makes the analysis result closer to the real situation and greatly saves the working time. The numerical analysis technology used in the core of Moldex3D analysis is a new numerical analysis method developed especially for 3D model flow analysis—high energy volume method. This method not only has the advantages of traditional finite element analysis, but also greatly improves the accuracy, stability and analysis performance of 3D solid flow analysis. It is the core of 3D model flow analysis in Moldex3D.
- Moldex3D provides a high affinity and more user-friendly intuitive window interface. Using icon toolbar, it is very easy to operate. Users can easily choose the mold and plastic materials, and set the injection machine. Finally, users can intuitively get the analysis results, and make the final analysis report.
- There are nearly 5500 kinds of material databases available in Moldex3D, and the data is very complete. Suitable materials can be selected from the material library for analysis at will, or user's own material database can be established by using the interface input parameters provided. For the processing conditions, users can use the conditions suggested for different materials, or use the input interface provided by the software to input the molding conditions of each program. The setting is very convenient.
- Moldex3D uses the latest 3D stereoscopic display technology to quickly and clearly display more than ten kinds of results such as temperature field, stress field, flow field and velocity field inside and outside the model. The above analysis results can also be displayed by means of allelic line or allelic surface. What's more, the internal changes of the model can be viewed directly by cutting the section, so that the changes of internal and external variables of the solid model can be presented more clearly. In addition, the XY-Plot function can be used to examine the variation history curve of Spure variables in the processing process with time. Moldex3D also provides the function of animation. Through the way of 3D animation to show the flow of plastic in the cavity, users can more intuitively recognize potential problems in the design and manufacturing process. And users can quickly accumulate design and troubleshooting capabilities within using the computer mold test methods to test various solutions. Besides, it also provides a variety of display tools to make the graph enlarged, shrunk, rotated. And it can

change the angle of view, transparency, the light source and the color of the graph. In addition, it can output the graph into a graph file (.BMP) or directly paste to other software for use.

2.2.3 *Point Cloud Processing Software*

Point cloud processing software is a software that processes solid point 3D coordinates obtained by 3D scanner. In reverse engineering, the point data set of product appearance surface obtained by measuring instrument is also called point cloud. Usually, the number of points obtained by 3D coordinate measuring machine is relatively small. And the distance between points is relatively large, which is called sparse point cloud. the number of points obtained by 3D laser scanner or photographic scanner is relatively large and relatively dense, which is called dense point cloud. Sparse point cloud or dense point cloud is the basis of reverse modeling, and there are many kinds of special reverse software that can edit and process point cloud, such as Geomagic, Imageware, Copycad and Rapidform, etc.

(1) Geomagic

① Overview of Geomagic

Geomagic Studio is a reverse engineering and 3D detection software. It creates good polygonal or mesh models from the lattice models obtained by object scanning, and converts them to NURBS surfaces.

② Application scope of Geomagic

Currently, software and services of Geomagic are used in a wide range of fields, such as automobiles, aviation, medical devices, and consumer products.

③ Features of Geomagic

The main features of this software are to support the reading and conversion of various file formats, the pretreatment of massive point cloud data, and the intelligent NURBS configuration, etc. The details are as follows.

- a. Geomagic Studio adopts the point cloud data sampling simplification algorithm, which overcomes the disadvantages of other similar software in the operation of point cloud data, such as slow operation speed and slow display of software graph topology. and its user-friendly interface design makes the operation very convenient [11].
- b. Geomagic Studio simplifies workflows for beginners and experienced engineers. with automated features and simplified workflows, user training time is reduced, and tedious, labor-intensive tasks are avoided. Compared with traditional computer-aided design (CAD) software, its production efficiency can be up to ten times higher when processing complex or free-form shapes. So,

to customize the same production model, it will only take minutes for using Geomagic Studio while taking days are needed for using traditional methods (CAD).

- c. Geomagic Studio also features high precision and compatibility. It can be used with all major 3D scanners, computer-aided design (CAD) software, conventional graphics software and rapid equipment manufacturing systems.
- d. Geomagic Studio allows users to work between physical objects and digital models, and close surfaces between objects and software models.
- e. Geomagic Studio provides a variety of modeling formats, including the mainstream 3D data formats: point, polygon, and heterogeneous rational B-spline surface (NURBS) models. The data integrity and accuracy ensure that high-quality models can be generated.

(2) Imageware

① Overview of Imageware

Imageware was produced by American EDS company, then acquired by German Siemens PLM Software, and now merged into its NX product line. It is a famous reverse engineering software. The software modules mainly include Imageware TM basic module, Imageware TM point trimming module, Imageware TM evaluation module, Imageware TM curved surface module, Imageware TM polygonal molding module and Imageware TM inspection module.

② Application scope of Imageware

Imageware is widely used in the design and manufacture of automotive, aviation, aerospace, consumer appliances, molds, computer parts, and more due to its powerful point cloud processing capabilities, surface editing capabilities, and Class A surface construction capabilities.

③ Features of Imageware [12]

- a. Imageware can receive data from almost all scanning devices, and can also input data in other formats such as G-Code and STL.
- b. Because some parts are too complex to get all the data in one scan, multiple scans are needed. Imageware can align and merge the read point cloud data to create a complete point cloud.
- c. Imageware provides multiple methods to generate curves from points. The user can select the curve generation method and select the appropriate parameters based on accuracy and smoothness requirements. Imageware provides diagnostic methods including display normals, radius of curvature, and comparison of control points to determine the smoothness of a curve. Imageware also provides the ability to modify the curve, change its continuity with adjacent curves, or extend the curve.

- d. Imageware offers a variety of ways to create surfaces. Users can create surfaces directly from points. And users can create surfaces by using curve through skinning, sweeping, four boundary lines, curve mesh blending and other methods. Combining point and curve information to create surfaces is available as well. When generating the surface, it can check the accuracy, smoothness and continuity of the surface in real time.

(3) Copycad

① Overview of Copycad

Copycad is a powerful reverse engineering system software produced by British DELCAM company. It can produce 3D CAD models from existing parts or actual models.

② Application scope of Copycad

Copycad is widely used in automotive, aerospace, shoe, mold, toy, medical and consumer electronics manufacturing industries.

③ Features of Copycad [13]

- a. The software provides a series of integrated tools to generate CAD models from digitized point cloud data, and to receive data measured by CMM, Sensors and Laser Scanners.
- b. Simple user interface enables users to master its functions and operations in the shortest time.
- c. Users of Copycad can quickly edit digital point cloud data, and create high quality and complex surfaces. The software can be used in many ways to form smooth, multifaceted block surfaces conforming to specified tolerances. Besides, it has the ability to guarantee the continuity of tangency between adjacent surfaces.

(4) Rapidform

① Overview of Rapidform

Rapidform is one of the four largest reverse engineering software in the world produced by INUS Company in South Korea. This software provides a complete set of tools for model segmentation, surface generation and surface detection. Therefore, users can easily apply the previously constructed curve grid to the new model reconstruction process after scaling [14].

② Application scope of Rapidform

Rapidform software is mainly used for surface modeling of measurement, scanning data and medical image modeling based on CT data. It can also complete measurement modeling of artworks and advanced graphic generation.

③ Features of Rapidform

- a. The software has a multi-point cloud data management interface. Advanced optical 3D scanners generate huge amounts of data that require expensive

computer hardware to process. Now Rapidform offers memory-management technology (using fewer system resources) to reduce the time to process the data.

- b. Multi-point cloud processing technology of Rapidform can quickly process large point cloud data. Both sparse point clouds and jump points can be easily transformed into rather good point clouds. The software also provides point cloud filtering tools and technology to analyze surface deviations to eliminate undesirable point clouds created by 3D scanners.
- c. Of all reverse engineering software, Rapidform provides the fastest and most reliable calculation method for 3D and 2D processing. It can quickly calculate polygonal surfaces from point clouds. Rapidform handles unordered points as well as ordered points.
- d. Rapidform supports color 3D scanners, to generate optimal polygons and image color information into the polygon model. In the process of surface design, the color information will be completely preserved, or the RP molding mechanism can be used to make a model with color information. Rapidform also provides color editing, which allows users to edit the model directly to colors they like.
- e. Rapidform provides point cloud merge function. Users can easily merge various point cloud data.

2.2.4 3D Printing Slicing Software

The 3D printing slicing software is mainly a model discretization and layering software developed for 3D printing equipment. At the same time, the type of printer can be selected in the slicing software to set the printing parameters, such as the filling rate, temperature and printing speed of the model. At present, the slicing software which is widely used and convenient to operate are Cura, MakerBot, XBuilder and so on. The quality of slicing software will directly affect the quality of printed items.

(1) Cura

Cura is an open-source software developed by Ultimaker company for 3D printing model slicing. Designed to be highly integrated and easy to use, it works on Windows, Mac OSX, and Linux platforms, and can be configured for a variety of 3D printing device types. Make CuraEngine that is developed by C++ integrated with Python language as the slicing engine [15]. However, the interface is relatively professional, which is not recommended by beginners.

Compared with similar open source products Slic3r and Skeinforge, Cura's advantages are: fast slicing speed, stable slicing, inclusive of 3D model structure, and less setup parameters.

(2) Makerbot

Makerbot is a slicing software developed by American Makerbot Company. The software is easy to operate and master. When running the software, slicing can be done in just a few steps [16].

(3) XBuilder

XBuilder3.0 is a Chinese version software independently developed by XiRui 3D printing technology, which is completely Chinese, simple in interface and easy to operate, and supports commonly used 3d format files such as ".stl,.gcode,.obj" [16].

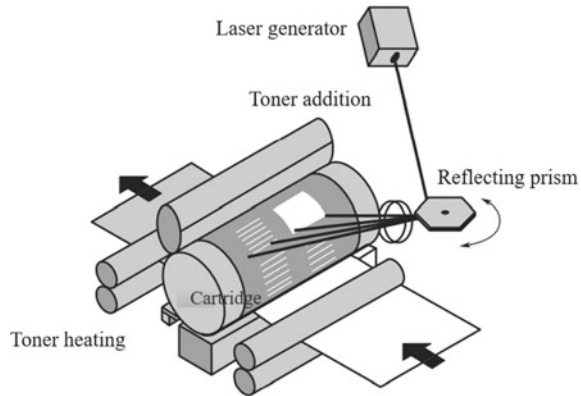
2.3 Raw Material Preparation and Plasticization

(1) Conceptual analogy of "toner cartridge"

One of the most important components in a common printer is the "toner cartridge". The toner cartridge, also known as the photosensitive drum, is generally composed of a basic substrate made of aluminum and a photosensitive material coated on the substrate. In the laser printer, more than 70% of the imaging components are concentrated in the toner cartridge which determines the printing quality to a large extent.

The toner cartridge is a cylinder coated with an organic material (selenium, a rare element) that is preloaded with electrical charges. When light hits the toner cartridge, a resistive reaction will occur at the irradiated site. The data signals control the emission of the laser, and the scanning light on the surface of the toner cartridge is constantly changing. So there are areas where the resistance is reduced and the charge is lost, and areas where the light is not hit but the charge remains. Finally, a latent image composed of electric charges is formed on the surface of the drum. The toner in the toner cartridge is a kind of fine resin particles with charge. The toner charge is opposite to the charge polarity on the surface of the drum. When the charged toner drum surface passes the inking roller, the charged parts adsorb the toner particles. As a result, the latent image becomes a real image. As the toner cartridge rotates, the printing system transmits the paper, which carries a much stronger charge of the same polarity as the surface of the toner cartridge. Then, the paper passes through the toner cartridge, which attracts the toner on the surface of the toner cartridge. Finally, the image is formed on the surface of the paper. At this point, the toner and the printing paper are combined only by the attraction of the electric charge. Before the printing paper is sent out of the printer, the toner is melted by high temperature heating and solidified on the surface of the paper during the cooling process. After the toner is attached to the paper, the surface of the toner cartridge continues to

Fig. 2.3 The working principle of laser printer toner cartridge



rotate through a cleaner to remove any remaining toner for the next printing cycle. Its working principle is shown in Fig. 2.3.

From the toner cartridge working principle can be seen, the toner cartridge not only undertakes the “raw material transportation and melting” function, but also plays the “molding” function. It is the core component of the ordinary printer.

For 3D printing technology, take fused deposition modeling(FDM) as an example. The thermoplastic filamentous material is sent to the hot melt nozzle by the wire feeding mechanism. Then it is heated in the nozzle, melted into a semi-liquid state, and then extruded, selectively coated on the worktable, rapidly cooled to form a thin sheet profile, and then stacked layer by layer to form a three-dimensional entity. The wire feeding mechanism and the hot melt sprinkler head form the “toner unit” of the 3D printer, which is stacked layer by layer under the three-dimensional movement of the workbench or nozzle.

For 3D copying technology, take injection molding as an example. After plasticizing in the heating barrel of the injection device of the injection molding machine, the plastic is injected into the cavity of the closed mold by the plunger or the reciprocating screw, and the products are cooled and solidified. The injection device and the mold constitute the “toner cartridge” of the 3D copier. The injection device plays the role of conveying raw materials and melting, and the mold plays the role of forming. The molten plastic enters the mold cavity, undergoes pressure holding, feeding, cooling and solidification to form a product. The plasticizing quality of the material has an important effect on the precision of the final product.

(2) Plasticizing quality control of raw materials

Screw plasticizing system is a basic device for thermoplastic polymer processing. Because of its excellent plasticizing ability, it is widely used in various plastic machinery, such as injection molding machine, extruder, etc. [17]. Screw plasticizing device mainly includes screw, barrel, heating and cooling system, driving system, etc. As one of the important components of plasticizing device, screw plays a key role in the plasticizing quality and temperature uniformity of polymer melt, and the temperature distribution of polymer melt ultimately affects the quality and yield of

polymer products [18]. The rapid development of modern manufacturing industry requires more and more high molding accuracy and production efficiency of plastic parts. For example, high-end plastic products, such as microlens and microfluidic chips, which adopt traditional screw configuration. Due to uneven plasticization, it is difficult to fulfil requirements [19].

The temperature distribution of polymer in screw plasticizing system ultimately affects the quality and yield of polymer products. Compared with general fluids, polymer melts exhibit high viscosity, non-Newtonian properties, and their physical properties are easily affected by temperature and pressure. All of these can easily cause fluctuations in the melt quality, and make it particularly difficult to effectively control the temperature and the uniformity of the temperature difference in polymer processing.

Taking injection molding machine as an example, uneven plasticization of materials is often the direct factor leading to defects of precision injection molding products. Due to the significant friction heat generation and poor thermal conductivity of the polymer, the uneven distribution of physical temperature in the plasticizing process seriously affects the quality of the molded products. For example, poor plasticizing will make molten material poor fluidity, resulting in products such as underinjection, dents and other defects. It can also make the material filling too much or insufficient, causing cracking, warping and deformation of products. In addition, because the local temperature is too high, the material may be overheated and decomposed. Therefore, improving the plasticizing quality and temperature uniformity of polymer in screw plasticizing system is one of the most effective methods to reduce the defects and improve the accuracy of polymer products.

The effective control of polymer processing temperature and uniformity of temperature difference has become an urgent problem in this field. To solve these problems, experts, and scholars from all over the world, starting from the traditional extrusion theory, have studied from the Angle of changing shear rheology or tensile rheology. There are two main research trends. One is to improve the common screw and develop new screw, such as the separation screw [20], barrier screw [21], diversion screw [22], variable channel screw, etc. New mixing elements are designed to enhance the mixing performance in the plasticizing process, and interfere with the flow of the polymer to achieve the effect of convective mixing [23]. The other is to improve the operating conditions, such as high-speed extruders, electromagnetic dynamic plasticizing extruders and screw under the action of vibration force field [24, 25].

The author's team proposed the field cooperative screw based on melt calculus and field cooperation theory, and studied the improvement of plasticizing quality and heat transfer characteristics of the screw plasticizing system from the perspective of heat transfer. The structure of the field cooperative screw is shown in Fig. 2.4. A certain length of screw is equally divided into division grooves along the circumferential direction. The entrance of the single material flow into multiple strands, and the exit of the multiple strands of material flow into a single strand. 90° reverse surface were designed in the dividing groove, so that the polymer could move in the axial direction while being torsional under the guidance of the dividing edge and barrel. The material originally located at the bottom of the dividing tank is moved to the top

of the dividing tank to strengthen the radial convection of the polymer and improve the synergistic effect between the velocity field and the heat flow field. It is also used to realize the purpose of strengthening the mass and heat transfer and improving the melt plasticizing quality and melt temperature uniformity.

The author simplifies and expands the theoretical model, and simulates its temperature field and velocity field. The structure expansion of ordinary screw and field cooperative screw is shown in Fig. 2.5. The velocity distribution and temperature distribution are respectively shown in Figs. 2.6 and 2.7. The results show that the field coordination screw structure changes the velocity field distribution, and the melt rolls and spirals under the viscous action of torsion surface and barrel, which achieves the enhanced mass transfer. At the same time, the coordination between the velocity field and the temperature gradient field is better, and plays the role of enhancing heat transfer.

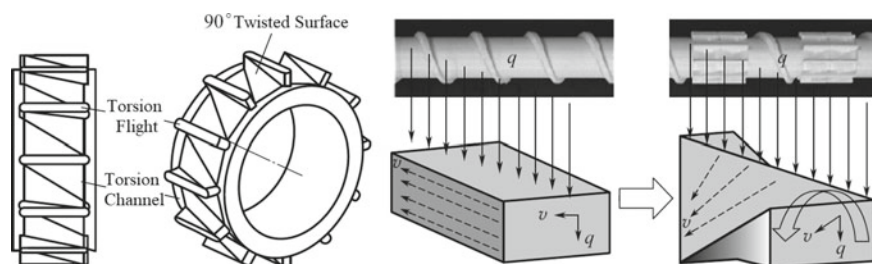


Fig. 2.4 Physical model and feed flow model of field cooperative screw

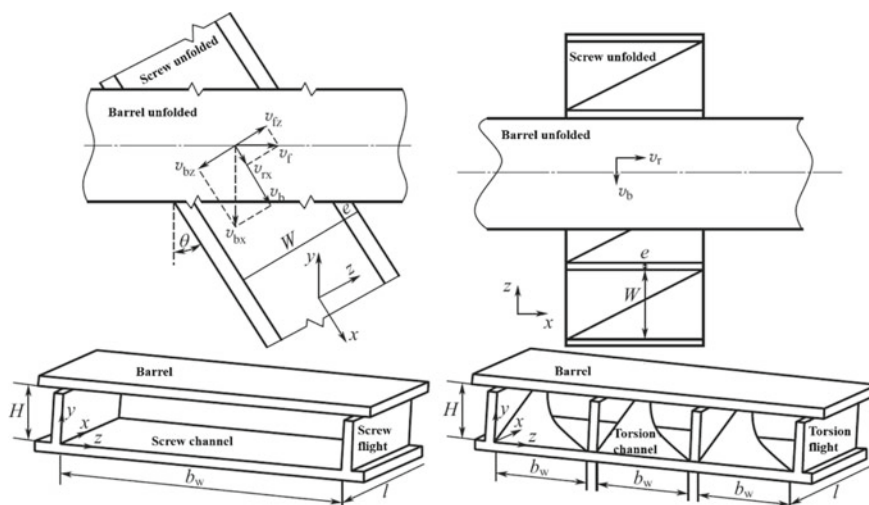


Fig. 2.5 Structure expansion of common screw (left) and field cooperative screw (right)

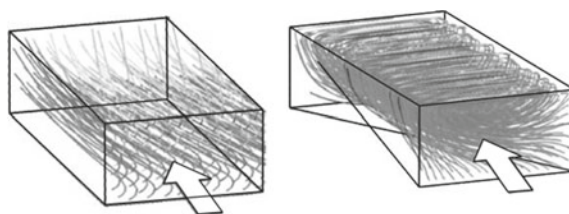


Fig. 2.6 Velocity distribution of common screw (left) and field cooperative screw (right)

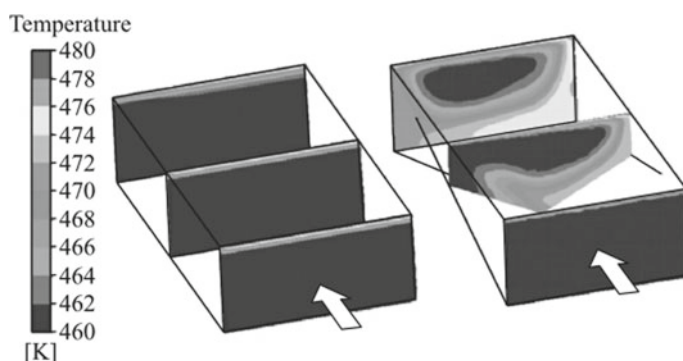


Fig. 2.7 Temperature distribution of common screw (left) and field cooperative screw (right)

2.4 Mold Design and Manufacture [26]

Mold is an important process equipment in industrial production. It is used to form various products with a certain shape and size. It is the core component of 3D copying technology. A variety of molds is widely used in a variety of material processing industry, such as metal products forming die casting mold, forging die, casting mold, non-metal products forming glass mold, ceramic mold, plastic mold, etc.

Using mold to produce parts has a series of advantages such as high production efficiency, good quality, saving energy and raw materials, low cost and so on. Mold forming has become an important means of contemporary industrial production, and is an important method to realize three-dimensional field entity copy.

There is a direct relationship between plastic products and molds. Mold shape, dimensional accuracy, surface roughness, parting surface position, demolding way have a great impact on the product's dimensional accuracy, appearance quality and so on. The temperature control mode of the mold, the pouring point and the position of the exhaust groove have an important influence on the condensed structure of the plastic parts, such as crystallization and orientation, and the physical and mechanical properties, residual stress. They also have an important influence on the defects of various products such as bubbles, dents, scorching and welding marks.

When designing the injection mold, it is necessary to consider not only the flow behavior, cooling behavior and shrinkage deformation of the plastic melt, but also the structural problems of the mold manufacturing and assembly. There are following several aspects of the main content of injection mold design.

- ① According to the rheological behavior of the plastic melt and the flow resistance of the passage and the cavity, the filling order was obtained through analysis. At the same time, considering the problems of the plastic melt being shunt and re-fused in the mold cavity, and the problems of the original air derived from the mold cavity, the position of the weld mark was analyzed to determine the number and position of the gate. In addition to using empirical or analytical methods to analyze in this regard, some CAE software with flow analysis at home and abroad can make a more accurate simulation of the mold filling process. The plastic properties database can provide a variety of data for rheological analysis, etc. For simpler products, a judgment may also be made by experience or simple calculation.
- ② According to the thermal property data of the plastic melt, the shape of the cavity and the arrangement of the cooling channel, the change of the temperature field of the products in the process of holding pressure and cooling is analyzed, so as to solve the shrinkage and feeding problems of the products and reduce the residual stress and warping deformation caused by the uneven temperature and pressure, the inconsistency of crystallization and orientation. At the same time, as far as possible to improve the cooling efficiency, shorten the molding cycle, which also has some mature CAE cooling analysis and stress analysis software, to help mold designers to carry out quantitative analysis. For simple symmetrical products can also be analyzed and determined by experience.
- ③ The problems of demolding and core-pulling can be solved by experience and theoretical analysis. At present, great efforts are being made to develop computer expert system software based on empirical and theoretical calculations, so that the work in this field can be realized more quickly and accurately on computers.
- ④ Determine the parting surface of the product and determine the setting and combination of the cavity. The overall structure and parts shape of the mold should not only meet the requirements of mold filling and cooling, but also have appropriate precision, roughness, strength, stiffness, easy assembly and manufacturing, and low manufacturing cost. In addition to the design of molding parts by experience analysis and theoretical calculation, some special software and the calculation software of cavity wall thickness and stiffness strength can be used to solve these problems quickly on the computer.

These problems do not exist in isolation, but interact with each other and should be considered in a comprehensive way. The typical structure of an injection mold is described below.

(1) The typical structure of an injection mold

The structure of the injection mold is determined by the structure of the plastic parts and the form of the injection molding machine. As long as it is an injection mold,

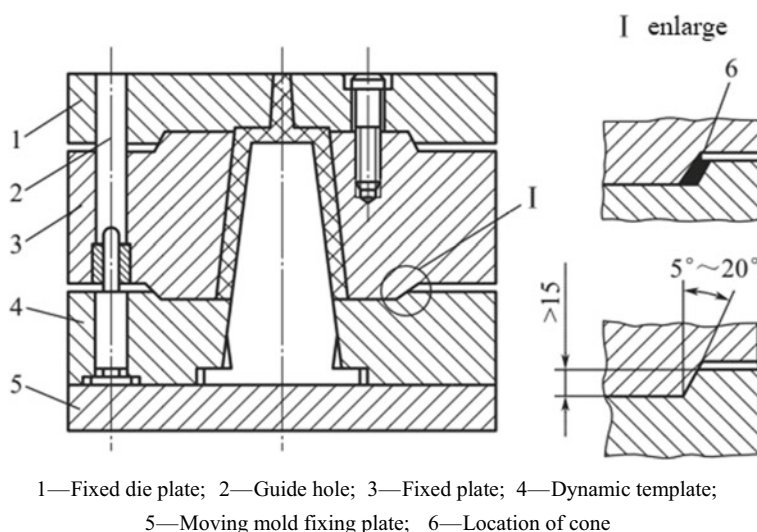


Fig. 2.8 Typical structure of injection mold

it can be divided into two parts: moving mold and fixed mold. When injecting, the moving mold and the fixed mold close to form the cavity and the gating system. When opening the mold, the moving mold and the fixed mold are separated, and the plastic parts are launched through the demolding mechanism. The fixed mold is installed on the fixed plate of the injection molding machine, and the moving mold is installed on the moving plate of the injection molding machine. Figure 2.8 shows the typical structure of an injection mold. According to the role of each component on the mold, it can be subdivided into the following parts.

① Molding parts

The cavity is the part of the direct molding parts, which is usually composed of punch (the internal shape of the molding part), concave die (the external shape of the molding part), core or molding rod, inserts, etc.

② Gating system

The flow channel that leads the plastic melt from the nozzle of the injection molding machine to the cavity is called the gating system, which is composed of the main stream channel, the shunt channel, the sprue and the cold material well.

③ Guiding parts

In order to ensure that the moving mold and the fixed mold are precisely aligned when the die is closed, the guide parts are provided. Usually there is a guide column, a guide hole (sleeve) or in the dynamic and fixed mold are respectively arranged on

the inner and outer cones of each other, some injection mold launch device in order to avoid movement in the process of launch skewed, but also with a guide parts.

④ Parting core pulling mechanism

Before being pushed out, plastic parts with lateral concave or side hole must be lateral parting, pull out the side of the concave and convex mold or pull out the side of the core pulling. Then, plastic parts can be released smoothly.

⑤ Push mechanism

A device for pushing plastic parts and gating system condensates out of a mold during mold opening.

⑥ Exhaust system

In order to discharge the original air in the mold cavity in the process of injection molding, which often set an exhaust slot at the parting surface. However, the exhaust capacity of small plastic parts is not large, and the parting surface can be directly used for exhaust. For most of the small and medium-sized molds, the fit gap between push rod or core and the mold can play an exhaust role, and there is no need to set an exhaust groove.

⑦ Mold temperature control system

In order to meet the injection molding process of the mold temperature requirements, the mold is equipped with cooling or heating system. The cooling system is generally set in the mold cooling water channel, heating system is in the mold or around the installation of electric heating components, molding to strive for stable and uniform mold temperature. At present, the emerging fast-changing mold temperature technology improves the flow behavior of the melt and improves the quality of the injection products through the rapid heating and cooling of the mold. The injection molding technology based on this is called rapid thermal cycle injection molding technology. The relevant content will be introduced in detail in the following chapters.

The design of injection mold mainly revolves around the above parts. Each mold can only be installed in the corresponding injection molding machine for production, so the mold design is closely related to the injection molding machine used. In the design of the mold, we should understand the technical specifications of the injection molding machine in detail, in order to design the mold in accordance with the requirements. From the perspective of mold design, we should carefully understand the technical specifications are as follows: the maximum number of injections of injection molding machine, maximum injection pressure, maximum clamping force, maximum thickness of the molding area, maximum and minimum thickness,

maximum travel distance, template installation mold screw hole (or T-slot) the position and size, injection molding machine nozzle hole diameter of ball head and the nozzle radius value, etc.

(2) CAE simulation analysis

With the improvement of CAD/CAE/CAM die technology and the application in die manufacturing, it has played a more and more important role in modern die manufacturing. CAD/CAE/CAM die technology has become the inevitable development trend of modern die manufacturing, and it provides a kind of effective auxiliary tool for the mold maker in a scientific and reasonable way, which make the mold maker before the mold manufacturing can use the computer to parts, mold structure, processing technology, cost and so on repeatedly modify and optimize, until the best results. All in all, mold CAD/CAE/CAM technology can significantly shorten the mold design and manufacturing cycle, reduce the mold cost, and improve the quality of the product, which is indispensable to modern mold manufacturing auxiliary tool. It has to do with “reverse engineering” and modern advanced processing equipment to form a modern popular and competitive in the die and mold industry necessary condition. It not only shortens the design and manufacturing cycle of the mold, but also improves the success rate of product development, and increases the value and market competitiveness of the mold.

As is known to all, in the process of mold design, it is necessary to fully consider the influence of melt shrinkage rate fluctuation and other factors, and give appropriate compensation to the mold forming size, which requires that the shrinkage rate used in the calculation is as consistent as possible with the shrinkage rate under the real forming conditions. Due to the low accuracy of the shrinkage rate in traditional mold design, it is often necessary to repeatedly test and repair the mold, which is not only time-consuming and laborious, but also increases the cost and restricts the production efficiency of the product [27–30]. Through the CAE numerical simulation method to predict the shrinkage and warpage of the parts, and then design and modify the mold structure or mold forming size, it can effectively improve the accuracy of the calculation of mold forming size, reduce The times of mold test and repair, and reduce the cost [31]. Therefore, the accuracy of the setting of physical parameters and processing parameters in the simulation software is particularly important for the prediction of simulation results.

At present, CAE software of plastic injection molding (such as Moldex3D and MoldFlow) provides many equations of state and the physical parameters of commonly used polymer materials. Whether the physical parameters of these materials are the same with those of the actual production process determines whether the numerical simulation results have practical significance. The test parameters of polymer materials mainly include polymer thermal expansion coefficient, specific volume, conversion point temperature and isothermal compressibility coefficient and so on. They play a very important role in guiding the application and processing of polymers. The related information can be obtained from the PVT relationship characteristic curves of polymers. Therefore, the PVT characteristics of polymer materials

play a very important role in the injection molding process of polymer products, especially for precision injection molding [31]. The PVT physical properties of polymer materials are used in CAE software such as Moldex3D and MoldFlow to simulate and analyze defects such as deformation and shrinkage during molding, and to guide the structural design of molds or products and the formulation of optimal injection molding process parameters [32, 33].

Therefore, PVT correlation properties of polymer was applied to computer simulation of injection molding processing, ensuring the material analysis software using database and the authenticity of the actual processing of materials, so that they can improve the structure of the mold or parts according to the analysis of the software, and really promote the actual injection molding processing and the quality of the products. The main functions of PVT characteristics in mold design are as follows.

① Instruct the calculation of forming dimensions

The molding size of the mold refers to the size of the cavity directly used to shape the plastic parts, mainly including the radial size of the cavity and the core (including the length and width of the rectangular or special-shaped core), the depth or height of the cavity and the core, the size of the center distance, etc. In the design of the mold must be based on the size of the product and precision requirements to determine the corresponding size and precision grade of the molding parts and give the correct tolerance value. The main methods for calculating molding size include average shrinkage rate method, limit size method and approximate calculation method. No matter which kind of calculation method, the formula needs to consider the shrinkage rate of plastic parts. When designing the mold, the difference between the estimated shrinkage rate and the actual shrinkage rate of plastic parts, and the fluctuation of the shrinkage rate during the production of products will affect the precision of plastic parts. This depends on the accuracy of the shrinkage rate simulated in the CAE software. The closer the shrinkage rate used in the calculation is to the actual product shrinkage rate, the higher the dimensional accuracy of the plastic parts.

② Instruct the modification of mold structure

Plastic products in the molding process may appear a variety of defects, such as warping deformation, bubble shrinkage, weld marks, multi-cavity flow imbalance and other problems. There are many reasons for these defects, such as unreasonable gate position or quantity, unreasonable runner layout or unreasonable runner size, etc. Through the injection molding CAE software simulation, can directly reflect the defects, and effectively repair the mold. The more accurate the simulation result is, the greater the reference significance is to mold design.

(3) Hot runner technology

Hot runner technology is an advanced technology applied to the pouring runner system of plastic injection mold. It is a hot trend in the development of plastic injection molding technology. The so-called hot runner molding means that the plastic sent to the sprue from the nozzle of the injection machine always keeps the molten state, and it does not need to be solidified to be taken out as waste when the mold is opened

each time. The molten material stuck in the gating system can be injected into the cavity when the injection is repeated.

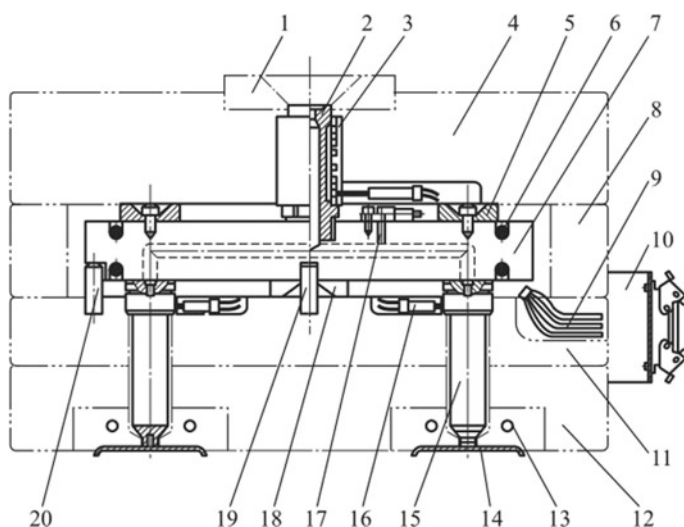
An ideal injection molding system should form parts of uniform density that are not affected by their runner, flanges, and gate inlets. Relative to the cold runner, hot runner to do this, it is necessary to maintain the melting state of the material in the hot runner and not be sent out with the molded parts. The hot runner process is sometimes called a hot collector tube system, or runner—less molding.

Basically, the hot runner can be thought of an extension of the barrel and the nozzle of the injection molding machine. The function of the hot runner system is to deliver the material to each gate in the mold.

The key of hot runner forming technology is the hot runner system. Figure 2.9 shows the structure of a typical hot runner system.

The hot runner system is located on the side of the die setting, which is mainly composed of the mainstream cup, the runner plate, the nozzle, the temperature control system components and the installation and fastening parts.

In theory, the main flow cup should have heating and temperature control device to ensure that the material is in the molten state. But because the main flow cup is short, the temperature compensation can be guaranteed through the heat conduction



- 1—Center locating ring ; 2—Main channel nozzle ; 3—Heaters of main nozzle ; 4—Fixed die plate ; 5—Pressure ring ; 6—Electric heating pipe bending ; 7—Channel plate (splitter plate) ; 8—plate ; 9—Heat-resistant conductor ; 10—Terminal block ; 11—Fixed mold splint ; 12—Fixed plate ; 13—Coolant passages ; 14—Injection molded parts ; 15—The nozzle ; 16—Nozzle lead line ; 17—Runway plate temperature measuring thermocouple ; 18—Bearing pad ; 19—Center locating pin ; 20—Anti-reverse pin

Fig. 2.9 Typical hot runner system structure

of the nozzle and the runner plate of the injection machine. In the actual production, sometimes there is no need to install the heating device, and the main cup and the runner plate are connected by thread. The outer diameter of the center positioning ring is matched with the positioning hole of the template on the injection machine.

The runner plate is suspended in the mold frame formed by the fixed template and the cushion plate, and the air gap is used for insulation. There is a pressure ring between the runner plate and the fixed template. In order to avoid the heat of the runner plate transfer to the given mold bottom plate, the pressure ring should be made of insulation materials. The pressure ring should also have extremely high strength, because it will withstand the thermal expansion stress of the channel plate when it is heated and the pressure of the injector nozzle. In addition to the central axis of the mold, between the channel plate and the fixed template is provided with a central positioning pin to ensure the accurate positioning of the channel plate, the channel plate edge is supposed to be provided with a stop positioning pin. The connection between the nozzle and the runner plate shall reliably prevent melt leakage. The heating element of the runner plate has a round bar heater and a tubular heater. At present, tubular heaters are more commonly used. Thermocouple is installed in the runner plate to detect its temperature, and the temperature regulator is used to control the disconnection and connection of the heating element circuit. The runner plate shall be well heated and insulated to ensure heater efficiency and effective temperature control.

The channel diameter of the hot runner nozzle should match the channel diameter on the runner plate, and the inlet of the nozzle should be smooth transition. There are two installation locations for the nozzle gate, one at the end of the nozzle housing and the other on the fixed plate. There are two main gate types, one is the main channel type gate, the other is the thimble type gate. The diameter of the nozzle's upper sprue needs to be carefully considered, as there is a risk of degradation due to the high melt temperature and high shear rate. All nozzles must be equipped with thermocouples. Their heating system must have its own control loop.

In order to prevent leakage, the role of thermal expansion should be included in the fastening and sealing of the runner plate, and the heat loss of the runner plate should be limited. As shown in Fig. 2.9, the pressure ring, flow plate and nozzle on the nozzle axis should have appropriate interference fit during injection heating to prevent leakage. In the case of high temperature thermal expansion, too much expansion force will crush and destroy the surface of fixed plate or fixed die plate. Therefore, the thickness of the pressure ring should be carefully checked.

(1) The structure of the hot runner system

The hot runner system is generally composed of three parts: hot runner element, electric heating element and temperature controller. The hot runner components include a mainstream runner cup, a runner plate and a nozzle, whose main function is to introduce molten material into the cavity. The heating and temperature control system of hot runner is mainly composed of heating element, monitoring point and control system. Heating elements are commonly used heating rod, heating ring, heating plate, interval heater, casting heater, embedded heater, etc., which require

high power density. The monitoring point is the temperature monitoring point located near the weak part or the working face in the entire flow passage, and the temperature is measured by thermocouple. The function of the control system is to regulate the temperature of the whole hot runner system, so that its temperature fluctuation can be controlled within a certain set range.

① Temperature control system

The hot runner system is a heat balance system. There is heat loss in the hot runner system in the working process. At this time, a heater is needed to compensate for its heating. In order to maintain the hot runner system in an ideal isothermal state, sensitive thermocouple and temperature regulator are needed to control the hot runner system effectively and accurately.

② The sprue cup

The sprue cup acts as the main flow channel of the cold flow channel, and directs the material from the nozzle of the injection machine to the flow channel plate. In theory, the main flow cup should have heating and temperature control device to ensure that the material is in the molten state. Because the main flow cup is very short, it generally does not need special heating, and its heat is usually obtained from the injector nozzle and the flow plate in the form of heat conduction.

Figure 2.10 shows the three main cups that are commonly used.

③ Melt transport and general arrangement of channel plate

Hot runner systems using runner plates generally have multiple nozzles, in order to ensure the quality of products, it is very important to realize the balance filling of plastic melt whether it is in the molding of the same product of the multi-cavity mold and different products of the multi-cavity mold, or a number of injection ports in the single cavity injection molding.

In the process of plastic melt filling, two ways are used to balance the filling mold.

- The design of a flow system with equal flow lengths to provide a natural or geometric equilibrium, as shown in Fig. 2.11, is called natural equilibrium (also called geometric equilibrium).

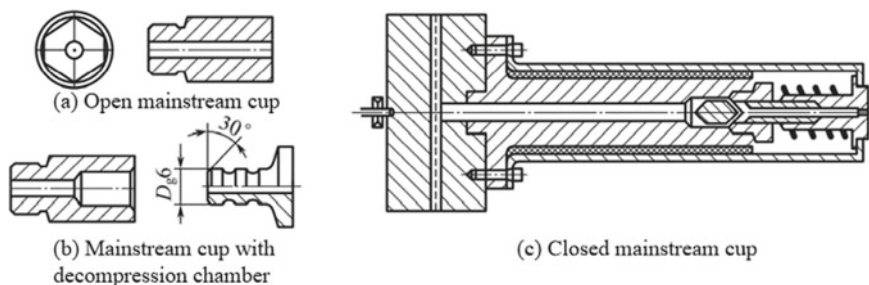


Fig. 2.10 Main track cup on the runner plate

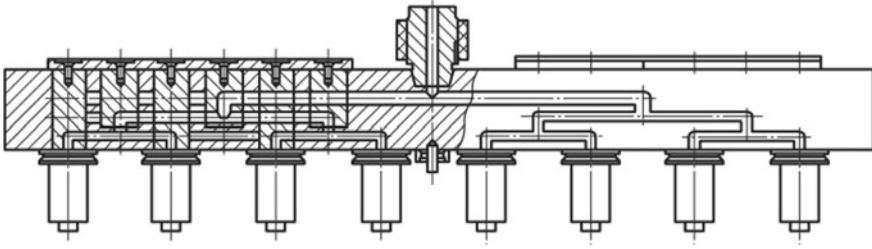


Fig. 2.11 The balance of nature

- b. The flow system is designed with the same pressure drop at each injection point, and the flow section is compensated for different flow lengths to obtain the balance calculated based on the rheological theory, which is called the rheological balance, as shown in Fig. 2.12.

④ The nozzle

a. Open nozzle

Some hot runner manufacturers also classify thimble nozzles as open nozzles, because they are heat flow closed gate compared to switch nozzle. Open nozzles here do not include thimble nozzles.

The gate diameter of the open nozzle is large, generally 1~4 mm. In practical production, the nozzle of this gate is easy to produce wire drawing and salivation, so it is not suitable for the plastic which is easy to produce wire drawing or salivation.

Open nozzles, as shown in Fig. 2.13, can be divided into two categories: Integral nozzle with direct gate [as shown in Fig. 2.13a] and Integral or partial nozzles with an insulated chamber [as shown in Fig. 2.13b and c].

b. Thimble nozzle

In hot runner injection production, the needle type open nozzle is replaced by the better performance of the thimble nozzle due to the easy wire drawing and salivating.

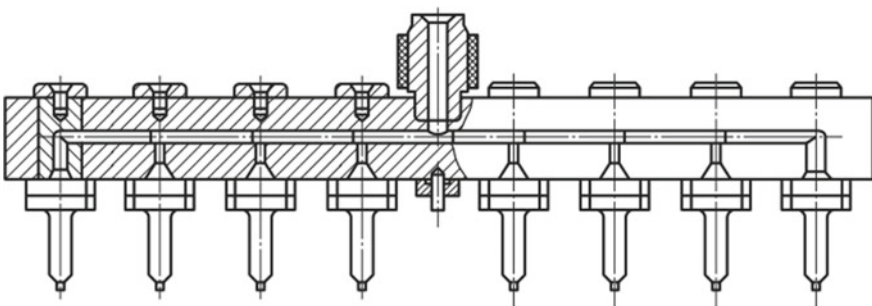
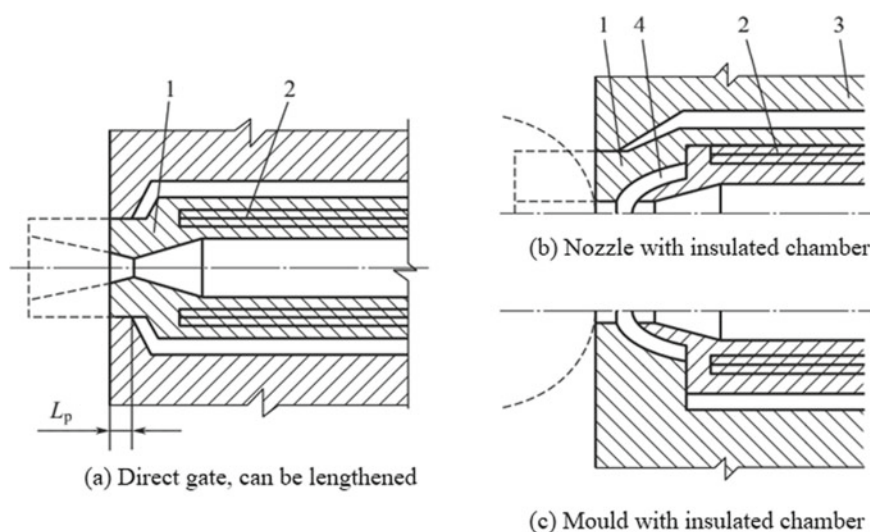


Fig. 2.12 Rheological equilibrium



L_p —Contact length between nozzle head and die hole ;
 1—Nozzle shell ; 2—The heater ; 3—Mold hole ; 4—Thermal insulator

Fig. 2.13 Structure of open nozzle

The thimble in the center of the gate helps prevent wire drawing and salivation of the melt, the use of thimble nozzles is increasing year by year. Because there is less waste on products and they are suitable for both amorphous and crystalline plastics. Its most notable feature is that the plastic melt is drained by a hot thimble to the gate, which has a small diameter and leaves little mark on the product. The temperature of the gate is easily controlled and can be used for injection of heat-sensitive plastics such as PVC and POM.

Due to the presence of thimbles, thimble nozzles are not suitable for shear-sensitive plastics, as well as plastics containing flame retardants or organic pigments, because it is easy to produce temperature rise and material decomposition in the sprue in the annular small gap.

Thimble nozzles can be divided into three basic types: heated torpedo thimble, torpedo thimble, and pipe thimble, as shown in Fig. 2.14.

c. Switch nozzle

Switching nozzle meets the requirements of large diameter gate design and eliminating residual waste at gate. There is a pillar pin which can move along the axial direction in the center of the switch nozzle, it can be driven by a spring, a cylinder or an oil cylinder. When the pressure holding stage is over, the pillar pin moves forward under the driving force, and the sprue in the nozzle is closed by the moving pillar pin. The nozzle closing control makes the pressure holding time consistent, ensures the repeated metering of the melt, and improves the precision of the products.

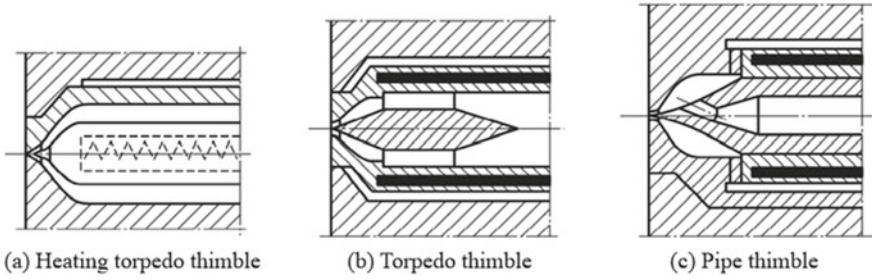


Fig. 2.14 Structure of a thimble nozzle

Because the gate is closed before the mold solidifies, the on-off nozzle can shorten the injection molding cycle compared to the open nozzle.

It is due to switch nozzle sprue diameter is large that the injection pressure loss is small and it reduces the loss of plastic molecular structure and shear stress and friction heat. Therefore, switching nozzles can be used for materials with low shear impedance, which will make it easier to pass through shear-sensitive plastics containing additives. Because the pressure drop is small, it can be used lower holding pressure, compared with other nozzles, injection parts of the internal stress is lower, and this nozzle completely prevent salivation or tensile defects.

As shown in Fig. 2.15, the structure of the switch nozzle can be divided into two types: partial type and integral type. Figure 2.15a shows a partially switched nozzle with a sprue set on the mold and a lower temperature in the sprue area, which is recommended for injection molding of amorphous plastics. Figure 2.15b is a monolithic switching nozzle. The gate hole seat is heated by the heater of the nozzle, which is suitable for the processing of crystalline plastics.

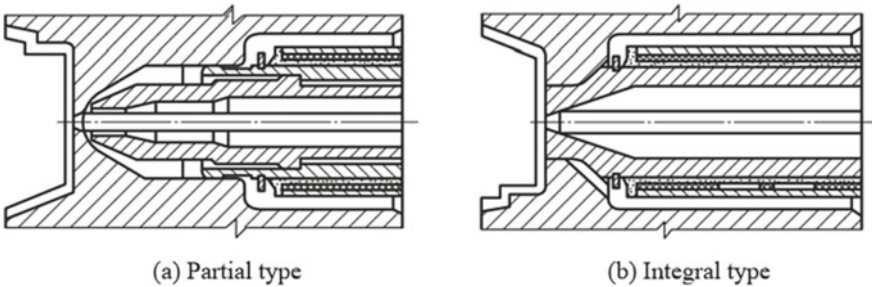


Fig. 2.15 Partial and integral switching nozzles

⑤ Advantages and disadvantages of hot runner die

a. Advantages of hot runner mold.

The hot runner mold is widely used in today's industrial developed countries and regions in the world. This is mainly because the hot runner mold has the following remarkable characteristics.

- Shorten the molding cycle of parts. In the cold runner mold, the maximum wall thickness of the product is often far less than the thickness of the main channel. When cooling, the main channel cooling lags behind the product, and the mold using the hot runner system has no main channel, and there is no cooling problem of the main channel, so the molding cycle can be greatly shortened and the injection molding efficiency can be improved. According to statistics, compared with the ordinary runner, the conversion of hot runner after the molding cycle can be generally shortened by 30%.
- Save on plastic materials. A large number of handles are produced in ordinary gating systems, and the weight of the condensate in the gating system may exceed the weight of the product in the production of small products. It is because the plastic in the hot runner mold has been in the molten state and the products do not need to trim the gate which is basically a waste-free process that it can save a lot of raw materials.
- Improve product consistency and quality. In the hot runner mold forming process, the plastic melt temperature is accurately controlled in the runner system. Plastic can flow into each cavity in a more uniform state, which can get the same quality parts. The quality of the sprue is good, the residual stress after demolding is low and the deformation of the parts is small. So many high quality products on the market are produced by the hot runner mold. For example, Motorola mobile phones, HP printers, Dell notebook computers in many plastic parts that people are familiar with are made by hot runner mold.
- Elimination of subsequent processes is conducive to production automation. After the plastic products are formed by the hot runner mold, there is no need to trim the sprue and take the condensing material handle, which is conducive to the automatic separation of the sprue and the product, and it is easy to realize the automation of the production process.
- Expand the application range of injection molding process. Many advanced plastic forming processes are developed on the basis of hot runner technology. Such as PET preforming production, multi-color co-injection in the mold, a variety of materials co-injection process, STACKMOLD, etc.
- Applicable material range is wide, and forming condition setting is convenient. Due to the improvement and development of the hot runner temperature control system technology, now the hot runner can not only be used for melting the PE, PP with wide temperature, but also can be used for processing the heat sensitive plastics with narrow temperature range, such as PVC, POM, etc. For PA which is easy to produce salivation, the hot runner can also be formed through the selection of valve nozzle.

- Enhance the function of injection machine. The plastic melt in the hot runner system is advantageous to the pressure transfer, and the pressure loss in the runner is small, which can greatly reduce the injection pressure and clamping force, reduce the time of injection and holding pressure, and make it possible to form large size plastic parts with long process on a small injection machine. Therefore, the cost of the injection machine is reduced, the function of the injection machine is strengthened and the injection molding process is improved.

b. Disadvantages of hot runner mold.

Although hot runner molds have many significant advantages over cold runner molds, mold users need to be aware of the disadvantages of hot runner molds. In summary, there are the following points.

- Mold costs are rising. The cost of hot runner system components is relatively expensive, the structure is relatively complex, the machining cost is high, and the cost of the mold is greatly increased. Sometimes the cost of hot runner system will exceed the cost of the cold runner mold itself. If the product production is small, the choice of hot runner system may outweigh the gain and loss.
- Hot runner mold production process equipment requirements are high. Hot runner mold needs precision processing machinery to ensure that the hot runner system and mold are very strict, and a series of problems such as mold material expansion should be taken into account. If the cooperation is not good, the phenomenon of overflow and gate freezing will occur, which leads to the decline of plastic product quality and serious inability to produce.
- Complicated operation and maintenance. Compared with cold runner mold, hot runner mold is more complicated to operate and maintain. Such as improper operation is easy to damage the hot runner parts, so that the production cannot be carried out, resulting in huge economic losses. For new users of hot runner die, it takes a long time to accumulate experience.

(2) Selection of hot runner mold

Although hot runner technology has been developed and applied for decades in the European and American countries where the mold manufacturing industry is more developed. But the traditional hot and cold runner dies still occupy a large proportion. For example, in the United States, it is estimated that the cold runner and hot runner each account for 50%. Some people say that the hot runner mold accounted for 60%, cold runner mold accounted for 40%. Which number is more accurate not to mention, at least we can see that if the cold and hot runner dies can coexist for a long time, they must have their own reason and application characteristics. For mold users and plastic injection molding manufacturers, one of the most basic questions is what time to consider the use of hot runner mold molding, when to consider the use of traditional cold runner mold molding.

In the demonstration of whether to use cold runner or hot runner mold forming, the main consideration of two factors: one is the economic cost of factors, the other is the technical requirements of factors.

① Economic cost considerations

Generally speaking, the production design and manufacturing cycle of hot runner die is longer than that of cold runner die, and there are more links involved. Therefore, in terms of the cost of the die itself, hot runner die is much more expensive. The economic advantages of hot runner die are mainly realized by reducing and eliminating production waste and realizing the automation of injection molding production.

If the production requirements of plastic products are very large (e.g., production requirements in the millions) and productivity requirements are high, the application of hot runner is very advantageous. Generally speaking, one of the most important factors affecting the injection molding cycle time is the cooling and curing time of plastic products. In the cold runner mold, the cross section size of the runner system is often larger than the wall thickness of plastic products, so the cooling time is longer. This often results in longer overall injection molding cycles. In contrast, the injection molding cycle can be significantly reduced on hot runner molds because there is no cold runner that requires a longer cooling time. In addition, cold runner molding often requires secondary processing operations, such as trimming the gate, recycling runner system waste, etc. The application of hot runner mold can avoid the problems of secondary processing operation and realize the automation of injection molding production.

For the plastic raw material is expensive, the production requirements are large and the recycling material is not allowed to process the project, the hot runner mold should be the first choice.

In the case of small production of plastic products, the choice of cold runner mold is economically more cost-effective, the mold delivery period is short, the use and maintenance are relatively simple. It is because hot runner components are expensive, and the production design and manufacturing cycle of hot runner mold is much longer than that of cold runner mold that for injection molding projects that require short, flat and fast, from the point of economic cost, it is not suitable to choose hot runner mold processing molding, but should consider cold runner mold.

Many mold companies will also combine the use of cold and hot runner mold. Before making a valuable hot runner mold, the cold runner mold is first used for small batch production of plastic products for the study and demonstration of production scheme. And the use of plastic products, after gaining experience and then according to the need to purchase hot runner system, change the original cold runner mold into hot runner mold.

For the company that just started to learn to use the hot runner mold, the initial investment and cost are relatively large. In addition to purchasing the hot runner system itself, it is needed to purchase a temperature controller. Because hot runner molds consume a lot of electricity, the electricity bill will increase dramatically. This

is an important economic cost factor in areas where power resources are scarce. User mastery of hot runner technology is critical, and adequate training of personnel is an expense.

Compared with cold runner dies, hot runner molds are more prone to various production failures. The use and maintenance of hot runner die are complicated. Hot runner components work under high temperature and high pressure dynamic load, and there are many factors that lead to their failure. Many hot runner components are also wearable parts and need to be replaced regularly, so hot runner users often need to buy spare components in addition to purchasing normal hot runner systems. This will increase the additional cost of use, and the chance of cold runner die failure is much less. For the failure of hot runner mold, it is often necessary for hot runner suppliers to send technical service personnel to help solve the problem smoothly, and these technical services are often charged services, which will also increase the cost of using hot runner die. At the same time, the economic benefit of plastic injection molding processing is mainly to rely on non-stop mass production to guarantee. Once there is a shutdown fault, economic loss is very big. Therefore, when deciding whether to use a cold runner or a hot runner mold, it is necessary to consider whether the shutdown failure of the hot runner mold can be smoothly resolved.

From the above discussion, it can be seen that there are many economic cost factors to decide to use hot runner mold, which should be considered comprehensively. Generally speaking, for large volume production requirements, expensive plastic raw material projects and experienced companies, should consider the use of hot runner mold. For projects with small production batch, insufficient technical experience of users and general product quality requirements, the traditional cold runner mold is more economical and cost-effective.

② Technical requirements considerations

As with any other economic activity, economy is of course the most important objective of injection molding. But at the same time, it is important to note that the technical requirements are also very important. Because for many, especially in recent years, the emergence of a variety of new injection molding process, with the traditional cold channel mold is technically impossible to achieve. In this case, although the cost of the hot runner mold is relatively high, it is the only choice technically. At the same time, the hot runner technology also improves the traditional injection molding process to a new height. After applying hot runner technology, die design is more flexible and diverse. The original cold runner cannot do the design scheme, but now the use of hot runner can achieve.

③ Application range of hot runner mold

- a. Types of plastic materials. Hot runner molds have been successfully used to process various plastic materials, such as PP, PE, PS, ABS, PBT, PA, PSU, PC, POM, LCP, PVC, PET, PMMA, PEI, ABS/PC, etc. Any plastic material that can be machined with a cold runner mold can be machined with a hot runner mold.
- b. Dimensions and weights of parts. The smallest parts made by hot runner die are below 0.1 g, and the largest is above 30 kg. It is widely used and flexible.

- c. The industrial area. Hot runner mold is widely used in electronics, automobiles, medical treatment, daily necessities, toys, packaging, construction, office equipment and other fields.

2.5 “Sample Copies”—Printing and Copying

After data collection, model analysis, raw material preparation and other preparatory work, the 3D printer or 3D photocopier can be used for “sample replication”.

2.5.1 *Polymer 3D Printing Process—FDM*

Fusion Deposition Molding (FDM) is a 3D printing process developed after LOM and SLA. This process extrudes fuses of filamentous materials, such as thermoplastics, wax or metal, through heated nozzles and deposits the melt at a fixed rate following a predetermined trajectory for each layer of the part. Every time one layer is completed, the worktable drops a layer thickness and deposits a new layer superposition, and so on. After this, the deposition of parts will be realized. FDM process does not need the support of laser system, is simple in operation, the molding materials used are relatively low in price, and the overall cost performance is high. It has become the main technical solution adopted by many open source desktop 3D printers, as shown in Fig. 2.16. FDM mechanical system mainly includes sprinkler head, wire feeding mechanism, movement mechanism, heating studio, work table 5 parts. The system model is shown in Fig. 2.17, and the process flow is shown in Fig. 2.18. The materials used in the melt deposition process are divided into two parts: one is the forming material and the other is the supporting material.

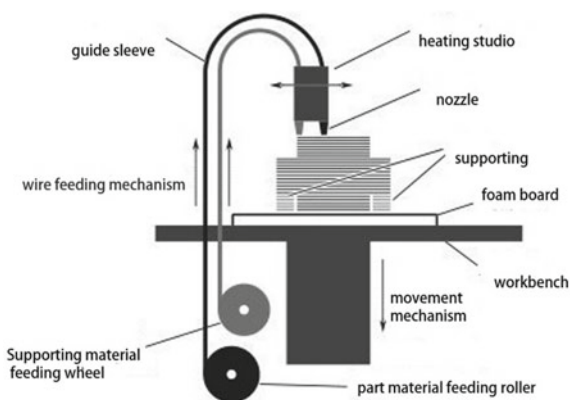
The hot melt wire (usually ABS or PLA) is first wound on the feed roller, and the roller is rotated by a stepping motor. The wire is sent out to the nozzle of the extruder under the action of the friction between the driving roller and the driven roller. There is a guide sleeve between the feeding roller and the nozzle. The guide sleeve is made of low friction material, so that the silk material can be transferred smoothly and accurately from the feeding roller to the inner cavity of the nozzle. There is a resistance wire heater above the nozzle. Under the action of the heater, the wire material is heated to the molten state, and then the material is extruded to the workbench through the extruder. After the material cools, the cross-section profile of the workpiece is formed. Every time one layer is completed, the worktable will drop a layer of height, and the nozzle will carry out the scanning spinneret of the next layer of section, so repeatedly layer by layer deposition, until the last layer. In this way, a solid model or part is stacked layer by layer from bottom to top.

In FDM molding, each layer is stacked on the previous layer, and the former layer plays the role of positioning and supporting the current layer. With the increase of the height, the area and shape of the laminar contour will change. When the shape

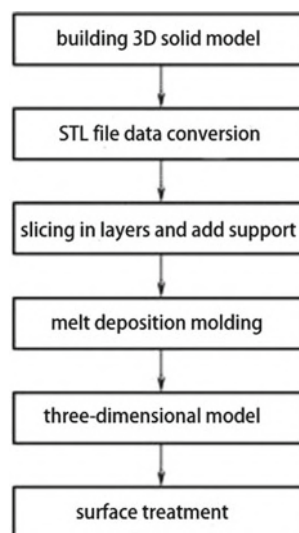
Fig. 2.16 FDM desktop 3D printer



Fig. 2.17 FDM system model



changes greatly, the upper contour cannot provide sufficient positioning and support for the current layer. This requires design some auxiliary structures—“support”, in order to ensure the smooth realization of the molding process. Now, two nozzles are generally used for independent heating, one is used to spray the model material to make parts, the other is used to spray the support material to do the support, the characteristics of the two materials are different, the support is removed after the production. In general, the filaments used for molding are relatively finer, more expensive, and less efficient at deposition. The filaments used to make the support material will be relatively thicker and less costly, but the deposition efficiency will be higher. The supporting material is usually water-soluble or has a lower melting point

Fig. 2.18 FDM process flow

than the molding material, so that the supporting structure can be easily removed by physical or chemical means during post-processing.

The wire feeding mechanism conveys raw materials for the sprinkler head, and wire feeding requires smooth and reliable. The wire feeding mechanism and the sprinkler head are combined with push–pull to ensure the wire feeding is stable and reliable and avoid wire breaking or nodulation.

The advantages of FDM rapid prototyping process: ① low cost, melt deposition molding technology with liquefier instead of laser, equipment cost is low, in addition, the use of raw materials with high efficiency and no toxic gas or chemical pollution, so that the molding cost is greatly reduced; ② The use of water-soluble support materials makes the removal of the scaffold structure simple and easy, and can quickly construct complex inner cavity, hollow parts and one-time forming assembly structures; ③ Raw materials are provided in the form of reel wire, which is easy to carry and quick to replace; ④ can choose a variety of materials, such as a variety of colors of engineering plastics ABS, PC, PPS and medical ABS; ⑤ raw materials in the forming process without chemical change, the warping deformation of the parts is small; ⑥ The prototype parts formed by wax can be directly used in investment casting; ⑦ FDM system is non-toxic and does not produce odor, dust, noise and other pollution, do not need to establish and maintain a dedicated site, suitable for office design environment use; ⑧ The material strength, toughness is good, can be assembled for functional testing.

The disadvantages of FDM rapid prototyping process are as follows: ① the surface of prototype has obvious stripe; ② the strength is small in the direction perpendicular to the section; ③ the need to design and manufacture support structures; ④ the molding speed is relatively slow, not suitable for the construction of large parts;

⑤ the price of raw materials is high; ⑥ The nozzle is easy to clog, inconvenient maintenance.

FDM rapid forming machine adopts the principle of dimension-reducing manufacturing, which decomposes the originally very complex 3D model into several 2D graphics according to a certain layer thickness, and then reverts the 3D solid sample by using the lamination method. Because the whole process does not need a mold, so it is widely used in the design and development process of automobile, machinery, aerospace, home appliances, communications, electronics, construction, medicine, toys and other products. Such as product appearance evaluation, scheme selection, assembly inspection, function test, user's sample order, plastic parts pre mold calibration design and a small amount of product manufacturing, etc. It is also used in government, universities and research institutes. Complex product prototypes that can take weeks or months to produce by traditional methods can be completed in a short time without any tools or molds using FDM.

2.5.2 Polymer 3D Copying Process—Injection Molding

In polymer 3D photocopying processing and molding, the first three steps are preparatory work, and the injection molding really starts to realize the product photocopying, so the injection molding machine is essentially a 3D photocopier. It is one of the most important and widely used methods for processing plastic products that the injection molding machine can quickly and efficiently copy large quantities of polymer products. With the continuous development of injection molding technology, there have been many new injection molding technology, used for molding products with special requirements, Such as injection compression molding, gas or water-assisted injection molding, resin transfer molding (RTM technology), reaction injection molding, foaming injection molding, multi-component injection molding, micro injection molding, rapid thermal cycle injection molding, photopolymerization injection molding, nano injection molding, etc.

(1) Injection compression molding (ICM)

In order to reduce the shrinkage of the products and improve the precision of the products, the traditional injection molding method is often used to increase the injection pressure, but the increase of the pressure will not only bring problems to the mold demolding, but also cause the residual deformation of the products due to the excessive pressure. The injection compression molding process was proposed in this environment [34].

① Principle and process of injection compression molding [35, 36].

The injection compression molding is also known as the secondary mold injection molding, is a combination of injection and compression molding technology. Compared with the traditional injection molding process, the prominent characteristic of injection compression molding is that the cavity space of the mold can be

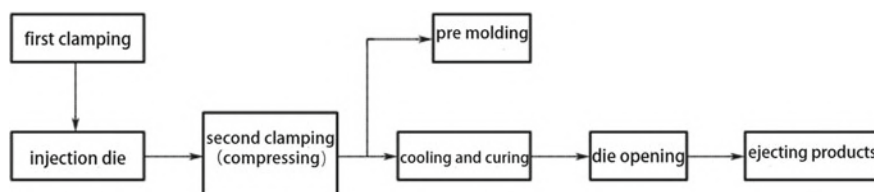


Fig. 2.19 Injection compression molding process flow

adjusted automatically according to different requirements. When the mold is closed for the first time, it does not completely close, but retains a certain gap. When the resin injected into the mold cavity shrinks due to cooling, a forcing force is applied from the outside to make the cavity size smaller, so that the shrinking part is compensated, so as to improve the quality of the product.

The technological process of injection compression is shown in Fig. 2.19. First, a small clamping force is used to make the mold close at a position where the thickness of the cavity is slightly greater than the thickness of the product wall, and then a certain volume of plastic melt is injected into the cavity. When the screw reaches the position set by injection, the clamping device immediately increases the clamping force and pushes the moving template with the male mold forward. The melt in the mold cavity is compressed by the male mold to obtain the precise shape of the mold cavity.

② Classification of injection compression molding [34].

Injection compression molding has four molding methods according to the geometrical shape of injection parts, surface quality requirements, as well as different conditions of injection molding equipment. They are sequential, synchronous, respiratory and local pressure.

a. Sequential ICM(SEQ-ICM): Sequential injection compression molding

Sequential means that the injection process and the mold process are carried out in sequence. As shown in Fig. 2.20, the mold is initially partially closed, leaving a cavity approximately twice the thickness of the part wall. After injection of molten material, the final complete closure of the die is performed and the polymer is compressed in the cavity. During this process, a streamline trace may be formed on the surface of the part due to the pause and stillness of the polymer flow between the completion of injection and the beginning of compression. The degree of visibility depends on the color of the polymer material, as well as the texture and material type of the part at the time of molding.

b. Simultaneous ICM (SIM—ICM): Simultaneous injection compression molding

Same with sequential ICM, the guiding part of the mold in synchronous ICM is also slightly closed at the beginning. The difference is that the mold starts to push and

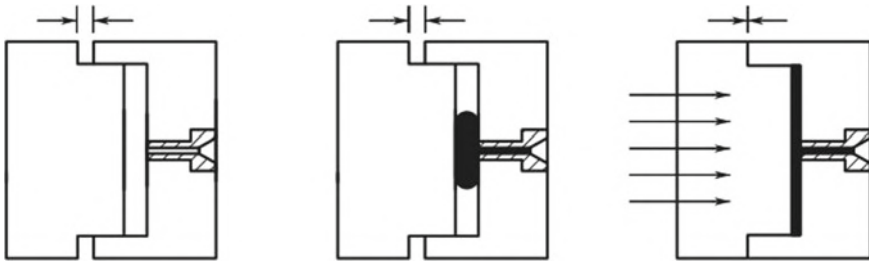


Fig. 2.20 Sequential ICM process

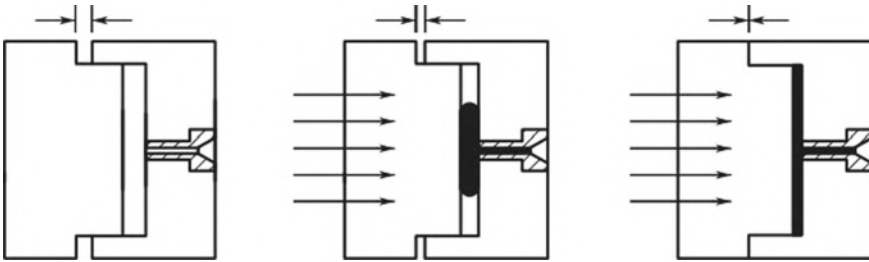


Fig. 2.21 Simultaneous ICM process

press at the same time as the material is injected into the cavity. Because the flow of the polymer is always in a steady flow state in front of it, it does not appear as sequential pauses and streamline traces on the surface. As shown in Fig. 2.21.

Since both methods leave a large cavity space at the beginning of the operation, the molten polymer may first flow into the lower side of the cavity due to gravity when the injection cavity has not encountered directional pressure, and may appear unwanted foam due to the temporary unpressurized state. This may be exacerbated by the fact that the larger the wall thickness of the part, the larger the cavity space, and the longer the flow length will increase the time period for complete die closure.

c. Breathing type ICM (breath-ICM): Breathing injection compression molding

With breathing ICM (intermittent), the mold is completely closed at the beginning of injection. As the polymer is injected into the mold cavity, the mold is gradually pulled apart to form a larger cavity space, and the polymer inside the mold cavity is always under a certain pressure. As the material approaches the filling cavity, the mold has begun to push in reverse until it is completely closed, further compressing the polymer to the desired size of the part. As shown in Fig. 2.22.

d. Selected compression ICM (Select-/com-I CM): Selected compression injection compression molding

With local pressure ICM, the mold will be completely closed. There is a built-in row head that presses from a local position of the cavity to the cavity during or after

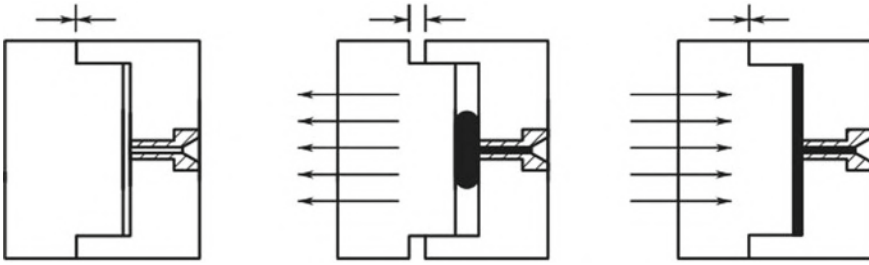


Fig. 2.22 Respiratory ICM process

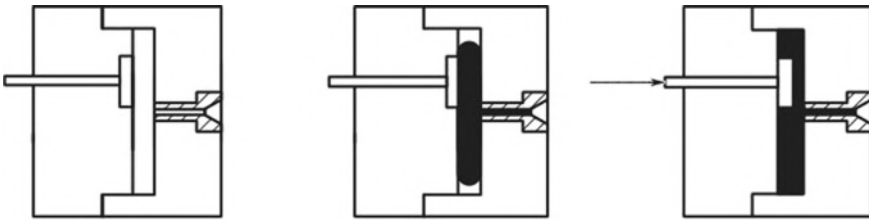


Fig. 2.23 Selected compression ICM process

polymer injection so that the larger solid part of the part is locally compressed and compressed thin. As shown in Fig. 2.23.

③ Advantages and disadvantages of injection compression molding [36]

a. The advantages of injection compression molding.

Injection compression molding can produce dimensional stable and basically stress-free products with low injection pressure, low clamping force and short production cycle. In traditional injection molding, high injection pressure must be applied to the nozzle of the injection machine in order to have enough pressure to push the melt flow and press the material. For thin-walled products, such as optical discs, there is usually a significant stress variation along the product direction due to high flow resistance, leading to residual stress and severe warping of the product. If injection compression molding is used, for most parts, the filling pressure is applied in the thickness direction, and a low filling/holding pressure is used to achieve a uniform pressure distribution, thus reducing residual stresses in the molding and warping of the part.

b. Disadvantages of injection compression molding.

Injection compression molds are relatively expensive and wear more during compression. Meanwhile, the injection machine requires additional investment, that is, the investment of the control module in the compression stage.

④ Applicable materials and applications [36].

Injection compression molding is suitable for all kinds of thermoplastic engineering plastics and some thermosetting plastics and rubber. Such as polycarbonate, polyether imide, acrylic resins, polypropylene, thermoplastic rubber and most thermosetting materials, etc. The main applications of injection compression molding include thin-wall parts and optical parts. For example, high quality and cost-effective CDs, DVDs and various optical lenses.

(2) Gas/water-assisted injection molding (GAIM/WAIM)

- ① The principle and process of gas or water-assisted injection molding. Gas-assisted injection molding (GAIM) or water-assisted injection molding (WAIM) are injected into the molten material along a specific nozzle or mold when the molten material is injected into the mold but has not been cured. Due to the action of pressure, the medium will penetrate the molten material, thus forming a cavity in the molten material, and then make the molten material fill the cavity. Then, the pressure of the medium is used to maintain the pressure, and finally the solidification is formed. Figure 2.24 shows the principle of gas-assisted injection molding (gas-in via nozzle).

The process of GAIM/WAIM can be divided into six stages [37].

- a. Plastic injection filling stage. This stage is almost the same as the conventional injection process, the only difference is that the molten material in this process does not normally fill the cavity at once, leaving a space of 4% to 30%.
- b. Switch delay stage. This stage is a very short period of time between the end of melt injection and the beginning of medium injection. Delay time has an important effect on the quality of GAIM products. The melt thickness fraction at the airway of the products can be changed by changing the delay time.

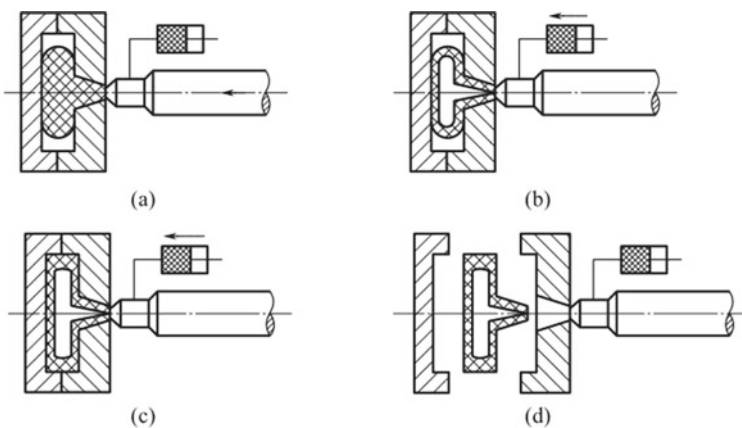


Fig. 2.24 Principle of gas-assisted injection molding

- c. Medium injection stage. This stage is a period of time from the beginning of the medium to the filling of the whole mold cavity. The time is very short as well, but it is the most core step in the whole process. It is very essential for the molding quality of plastic products, and many defects will occur if it is not properly controlled, such as cavitation, melt front blowing through, insufficient injection, and medium penetration into thinner parts.
 - d. Pressure holding cooling stage. The product depends on the pressure of the medium to hold the pressure at this stage. When the medium is water, the medium can also be very good for the product cooling, and ultimately shorten the molding cycle.
 - e. Medium discharge stage. Whether the injected medium is inert gas or water, it must eventually be expelled.
 - f. Ejection products. This stage is the same as conventional ejection injection.
- ② The advantages and disadvantages of gas-assisted injection molding and water-assisted injection molding

Although gas-assisted injection molding and water-assisted injection molding are similar, they have their own advantages and disadvantages, which are mainly reflected in the following aspects:

- a. Both technologies have obvious advantages in saving raw materials, preventing shrinkage marks, shortening cooling time, improving surface quality, reducing internal stress and deformation degree of products, and reducing clamping force. Both technologies have obvious advantages in saving raw materials, preventing shrinkage marks, shortening cooling time, improving surface quality, reducing internal stress and deformation degree of products, and reducing clamping force.
 - b. The common disadvantage of the two processes is that the equipment cost is high, the process parameters need to be strictly controlled, and the nozzle design is very complicated. Vents can cause surface quality problems for gas-assisted injection molding. For water-assisted injection molding, due to the characteristics of water, more problems need to be considered, such as how to determine the appropriate water temperature, water pressure, flow rate and the influence of water flowing in the melt on the quenching of material crystallization and the performance of plastic parts [38].
 - c. Compared with gas assist injection molding, water-assisted injection molding can produce hollow products with thinner and more uniform wall thickness, and with less material. Compared with gas assist injection molding, water assisted injection molding can produce hollow products with thinner and more uniform wall thickness, and with less material.
- ③ Application of gas-assisted and water-assisted injection molding process [39]

Gas-assisted injection molding and water-assisted injection molding are widely used in almost all plastic parts fields such as daily plastic products, furniture industry, toy industry, home appliance industry, automobile industry, etc. Among them, gas-assisted or water-assisted injection molding is especially suitable for hollow products,

wall thickness, wall thickness (different thickness of the section of the components) and large flat structure parts, such as handle, handle, etc.

(3) Resin transfer molding (RTM).

① Process and characteristics of transfer molding [40].

Resin transfer molding (RTM technology), also known as resin die-casting molding, is a process technology in which low-viscosity resin flows in a closed mold, infiltrates reinforced materials (glass fiber, carbon fiber, etc.) and solidifies. The technological process is shown in Fig. 2.25. Resin transfer molding has the following characteristics.

- RTM process consists of two steps: preforming processing and resin injection curing, which is highly flexible and combinative.
- The preforming technology of the reinforcement material is similar to the shape of the product, and the infiltration of the fiber resin can be cured as soon as it is completed, so a low viscosity and fast curing resin can be used, and the mold can be heated to further improve production efficiency and quality.
- Reinforcement material preforms can be chopped mat, continuous fiber mat, fiber cloth, wrinkle-free fabric, three-dimensional knitted fabric, and three-dimensional knitted fabric. Selective reinforcement, local reinforcement, hybrid reinforcement as well as embedded and sandwich structure can be used according to the performance requirements, which can give full play to the designability of composite properties.
- Closed mold resin injection method can greatly reduce the toxic resin harmful components to human body and the environment.
- RTM generally adopts low pressure injection technology (injection pressure $< 4\text{kgf/cm}^2$), which is conducive to the preparation of large size, complex appearance, smooth two-sided overall structure, and products without post-treatment.
- In the process, only resin is needed for cooling.

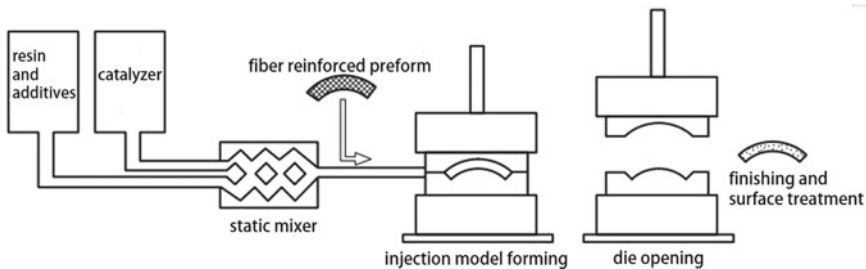


Fig. 2.25 Transfer molding (RTM) process flow

- a. Storage. The multi-component stock used in Reaction Injection Molding is usually stored in a specific reservoir (pressure vessel). When the stock is not molded, the stock usually circulates continuously in the reservoir, heat exchanger and mixing head at a low pressure of 0.2~0.3 MPa. For polyurethane, the temperature of the stock solution is generally 20~40 °C.
- b. Measurement. Before mixing, the original solution of different components needs to be accurately measured. Hydraulic quantitative pump is generally used for metering output.
- c. Mixture. Mixture is a key step in reaction injection molding. The quality of the product is largely determined by the mixing quality of the mixing head, and the production capacity is completely determined by the mixing quality of the mixing head.
- d. Mold filling. The filling speed of reactive injection molding is very high, so the viscosity of the original solution should not be too large.
- e. Curing. Curing is the most core stage of injection molding. Different from the cooling curing of traditional thermoplastic injection molding and the heating curing of thermosetting injection molding, reactive injection molding is solidified by means of melt collision, and the temperature of the mold wall is not much different from that of the melt.
- f. Ejection. After curing, the ejection product is the same as the conventional injection molding process.
- g. Post-processing. Reaction injection molding products need to be heat treated after ejection, to supplement the curing, the formation of a firm protective film, decorative film.

② Advantages and disadvantages of reactive injection molding

- a. Advantages of reactive injection molding: Reaction injection molding is one of the lowest energy consumption processes. The reaction liquid viscosity is low, the cavity pressure is small, the mold temperature is not high, and the energy consumption is very little, so the reaction injection molding has relatively low requirements on the mold equipment. It is easy to make thin-walled, lightweight products with good surface quality and high production efficiency and it is especially economical to produce large quantities and large sizes of products.
- b. Disadvantages of reactive injection molding. Because of the chemical reaction in the process, the mold and process design of reaction injection molding are quite complicated. For example, slow mold filling may lead to gel and under-injection, while rapid mold filling may produce turbulent flow, resulting in internal pores. Improper control of mold wall temperature or too thin wall thickness can lead to forming problems or cause material scorching. The material viscosity is low, easy to produce overflow, need to be trimmed. The isocyanate reaction requires special

environmental protection measures due to health problems. Reaction injection molds are much more difficult to recycle than thermoplastic resins.

③ Application of reactive injection molding

Reaction injection molding is commonly used to produce large, complex products, especially automotive internal and external components, such as bumpers, bumper panels, and door panels. Other automotive applications include fenders, armrests, steering wheels, window seals, etc. Non-automotive applications include furniture, commercial machine enclosures, medical and industrial equipment enclosures, agricultural and construction products, household goods, and recreational facilities.

(5) Foam injection molding [45]

Foaming technology refers to the physical and chemical methods to make plastic products to form a bubble structure of the molding method. The physical method is to directly inject gas to form the bubble pore structure, while the chemical method is to inject chemical foaming agent to decompose gas to form the bubble pore structure by chemical reaction. As one of the most important molding methods, injection foaming has attracted extensive attention from scholars at home and abroad in recent years. The foaming process of injection molding is completed in the mold. The paper mainly introduces the structural foam injection molding and microcellular foam injection molding which attract more attention.

① Structural foaming injection molding

Structural foaming material refers to a kind of foaming material with a tough and dense surface layer and a uniform microcellular foam structure inside. It is mainly used for engineering structural parts, such as copier bracket, base, building materials, etc. Structural foaming injection molding can be divided into three categories: low pressure foaming, high pressure foaming and two component foaming.

Low pressure foaming injection molding adopts under injection method, and the whole injection molding equipment is basically the same as the conventional injection molding equipment. It should be noted that the injection nozzle needs to be self-locking, and the surface of low-pressure injection foam products is rough, and the accuracy is not very high.

High pressure foaming injection molding adopts full injection method., so the mold needs to be slightly separated after the injection to complete the foaming process. At this time, it is necessary to add a secondary clamping device to the clamping system to ensure the smooth and clear surface of the high pressure injection foamed products.

The two-component injection foaming is usually through the same gate, using two injection equipment to inject the cortex and core material successively, in which the core material contains foaming agent. As with high pressure injection foaming, it is necessary to add a second clamping device. Moreover, as previously mentioned, the

two-component foaming injection molding machine is a kind of multi-component foaming, and its injection device needs two sets, and the structure is more complex.

② Microcellular foaming injection molding

Microcellular foaming is a concept put forward by Massachusetts Institute of Technology (MIT) in the 1990s. Its bubble size is usually a few microns. Microcellular foaming materials maintain the strength of polymer materials well, and can improve the mechanical properties of plastic very well. In recent years, a large number of scholars have developed a series of microcellular foaming injection machines based on the concept of MIT microcellular foaming. Such as the United States TREXEL company's MuCeLL microcellular foaming injection molding machine, IKV microporous injection molding machine from RWTH Aachen University, Germany, and The Er-goCell micro hole injection molding machine of Germany Demag Ergotech company. These microcellular foaming injection molding machines all have a common feature, that is, the foaming agent is directly injected into the end of the injection screw melt section, and evenly mixed with the melt. Therefore, airflow channels and other auxiliary devices need to be designed on the barrel. Figure 2.27 shows a microporous injection molding machine developed by the IKV Institute of RWTH Aachen University, Germany.

Arburg and IKV also jointly developed ProFoam, a physical pre-foaming technology. As shown in Fig. 2.28, the basic principle is that the raw material is foamed through low-pressure nitrogen before entering the barrel. The raw material is first added to the upper chamber of a pre-foaming device consisting of two pressurized chambers and a physical foaming agent (N₂) is added at low pressure (50 bar). Then the chamber gas valve is opened to let the raw material into the lower pressure

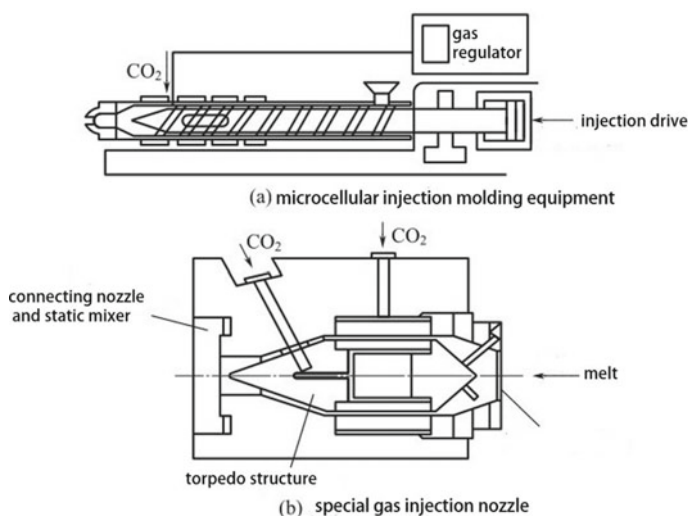


Fig. 2.27 IKV Microporous Injection molding machine

chamber and then locked, and the upper chamber continues to feed. When the lower chamber valve is opened, the raw material enters the plasticizing system, so that the physical foaming agent can be uniformly dissolved into the plastic melt. During the process of decompression, a uniform distribution of microporous structures can be produced inside the product. The advantage of this process is that there is no need to install additional shear and mixing functions on the screw. In particular, ProFoam has been used to produce foamed parts with long fiber reinforcements for improved mechanical properties. Compared with the traditional process, the parts produced can obtain the reinforcing fiber of longer average length. According to different materials, the surface quality can also be optimized by using variable mold temperature technology.

(6) Multi-component injection molding

① Process and characteristics of multi-component injection molding

Multi-component injection molding, as the name implies, it’s a kind of injection molding process in which two or more kinds of polymer materials are mixed to obtain the products [46]. As we are familiar with the injection molding, sandwich molding, coating molding, two-color and multi-color injection molding belong to the category of multi-component injection molding. According to the different characteristics of polymer, multi-component injection molding requires two or more sets of injection

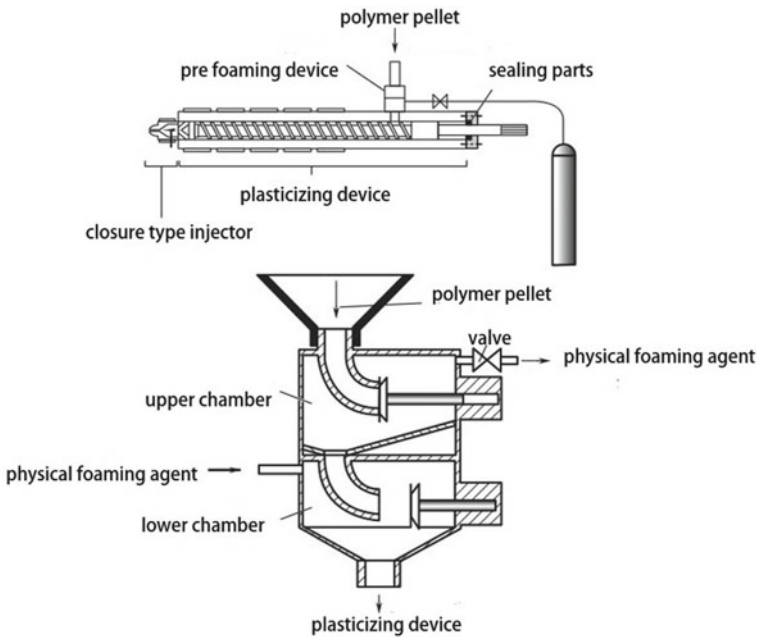


Fig. 2.28 Fundamentals of Arburg Physical Foaming Injection molding

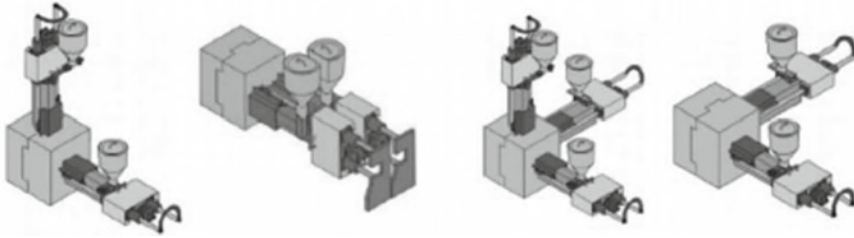


Fig. 2.29 Different arrangement of injection unit in multi-component injection molding machine

devices to work together which is different from the traditional injection molding process, as shown in Fig. 2.29, therefore, the structure of multi-component injection molding machine is more complex and needs more space, but at the same time, multi-component injection molding has many advantages that other injection technologies cannot compare with, for example, it can make the materials with different using characteristics or processing characteristics be composite formed; it can improve the handle feel and appearance of the product, and set a variety of functions in one; The product design time and molding cycle will be shorten; Also it can reduce or cancel the secondary-working and assembly after traditional injection molding.

According to the different combination forms of components in the molding process, multi-component injection molding can be divided into sequential injection molding and superimposed injection molding [47].

Sequential injection molding refers to the process of injecting materials into the mold cavity in a specific order. Generally, this process is realized by a special multi-component nozzle. The injection molding process is as follows: Firstly, make the first melting component inject into the mold cavity to form the surface layer of the product, then after a certain time, the switch valve of the multi-component nozzle is used to switch the position, and inject the second melting component to form the core part of the product.

Superimposed injection molding refers to a process in which a variety of components are injected together through different gates or channels or superimposed together. The main difference between superimposed injection molding and sequential injection molding is the change of mold. According to the different state of the material in the injection process, the superimposed injection molding can be divided into “melt / melt” injection and “solid/melt” injection. “Melting/melting” injection molding is also called co-injection molding, referring to the simultaneous injection of two or more molten components into the mold cavity through different gates. “Solid/ melt” injection molding refers to a method in which the first molten component is partially solidified, and then it enters the next molding position, and several molten components are injected after injection.

② Application of multi-component injection molding

Multi-component injection molding has developed rapidly in recent years, and its application has become more and more extensive. Its biggest advantage lies in the

Fig. 2.30 Miniature injection molding machine of Italy BABYPLAST company



production of products with layered structure and multi-color products, such as multi-color taillights of automobiles and buttons of equipment.

(7) Micro-injection molding

① Micro injection molding

Micro-injection molding is a process of injection molding micro-sized and micro-structured products, the products' size is generally micron level, the basic structure of the earliest micro injection molding machine is the same as that of a conventional injection molding machine, as shown in Fig. 2.30, it's the miniature injection molding machine of the Italian BABYPLAST company. However, due to the smaller and more precise injection equipment, its requirements are more stringent, which is specifically reflected in the following aspects [48, 49]:

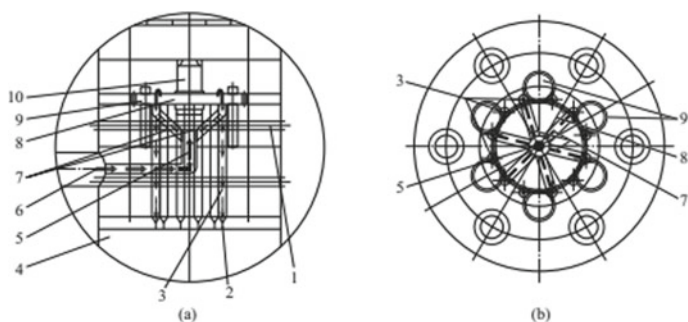
- a. High injection rate. The quality and volume of micro-injection molding parts are small, and the injection process must be completed in a short time to prevent the melt from solidifying and causing the parts to under-inject, so the injection speed is required to be high during molding. The injection speed of the traditional hydraulic-driven injection molding machine is 200 mm/s, the injection speed of the electric servo motor-driven injection molding machine is 600 mm/s, and the micro-injection molding process usually requires the injection speed of the polymer melt to reach 800 mm/s.
- b. Precise injection volume. The quality of micro-injection molding parts is only measured in milligrams, so the micro-injection molding machine needs to have a control unit for precise measurement of one-time injection in the injection process, the precision of quality control should reach milligram level and the precision of screw stroke should reach micron level. The traditional injection molding machine usually adopts the linear reciprocating screw injection structure, the error of injection is relatively large, which cannot meet the micro control of micro injection molding, so the screw plunger structure can be used.
- c. Rapid response capability. In the process of micro-injection molding, the injection volume is very small, and the movement stroke of the screw/plunger of

the corresponding injection equipment is tiny. Therefore, the driving unit of the micro injection molding machine must have a fast reaction speed, so as to ensure that the equipment can reach the required injection pressure rapidly.

- d. Fast-changing mold temperature technology. The requirement of high precision for size also makes it necessary to adopt the technology of fast-changing mold temperature for micro-injection molding, so that the mold can be heated and cooled rapidly. The specific scheme can be determined according to the process conditions.
- e. Material requirements. The polymers that can be used for micro-injection molding are usually engineering plastics and special engineering plastics.

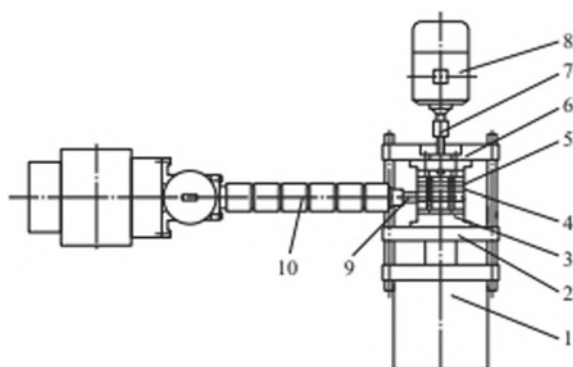
② Differential injection molding [50]

Differential injection molding is a new method of injection molding of micro products which break the antiquated thinking of “large equipment produces large products, small machines produce small parts” It was first proposed by the En-learn Laboratory of Beijing University of Chemical Technology, the principle of “producing small products with large equipment” is under the action of pressure, one melt is evenly divided into several melts. And it can measure the split melt which can achieve the results of separating one strand of melt into several strands, large melt into small melt, small melt into tiny melt. The core of differential system is melt differential pump, which has the same basic principle as planetary gear pump. Differential injection molding theory is to add differential system to traditional injection molding technology (shown in Fig. 2.31), in addition to the injection system of traditional injection molding machine, the melt plasticizing injection of polymer also needs the help of differential system, the differential system has the functions of melt diversion, transportation, pressurization and metering. The differential injection molding machine based on differential injection molding theory can realize the functions of multiple micro-injection molding machines.



1-Heating device; 2-Micro products; 3-Outlet; 4- Mold; 5-Inlet;
6-Spray nozzle; 7-Branch of inlet; 8-Driving gear; 9-Driven gear; 10-Drive shaft

Fig. 2.31 Differential system structure of differential injection molding machine



1- Clamping system; 2- Moving template; 3-Mold; 4- Differential pump; 5-Heating device; 6- Fixed template; 7-Coupling; 8-Driving motors; 9- Spray nozzle; 10- Plasticizing system

Fig. 2.32 Structure of differential injection molding machine

In differential injection molding, the melt pump is installed between the injection molding machine and the mold (shown in Fig. 2.32), so that the fluctuation of the injection direction can be isolated from the mold equipment. No matter whether the pressure at the pump inlet fluctuates or not, as long as the melt entering the pump can fully fill the teeth, the material can be transported to the mold with stable pressure and flow, so as to improve the stability of the system and the accuracy of the product. Melt pump is a kind of pressurization equipment, which can transfer the function of pressure stabilization and pressurization of screw metering section of injection molding machine to melt pump.

At present, the application of microsystem technology has expanded from micro-electronic components, micro optical instruments, micro medical instruments, micro sensors to disk read-write devices, ink-jet printing and so on. The development of micro- injection molding is more and more rapid. It has incomparable advantages in the manufacturing of micro structure components in a wide range of disciplines, such as microelectronics, micromechanics, micro optics, micromechanics, microfluidics, micro-thermodynamics, materials science, physics, chemistry and biology.

(8) Rapid heating cycle molding (RHCM)

For the conventional injection molding process, the requirements of mold temperature for the quality of plastic parts and injection production efficiency are contradictory. If the quality of plastic parts needs to be improved, the mold temperature should be increased as much as possible to eliminate a series of defects such as condensation layer. However, increasing the mold temperature will increase the cooling time and decrease the production efficiency. In order to solve this contradiction, a new injection molding process, rapid heating cycle injection molding, is proposed in the industry.

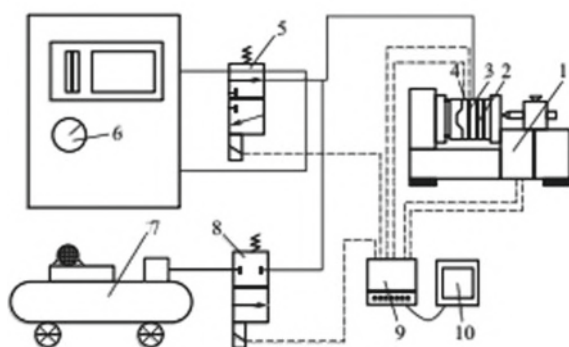
① Principle of rapid heating cycle injection molding

Rapid thermal cycling injection molding method is a new injection molding method based on dynamic mold temperature control strategy, which can realize rapid heating and cooling of mold, and implement closed-loop control of mold temperature [51].

The implementation is as follows: The mold is heated to a higher temperature before injection filling to avoid premature condensation of the melt in the filling, so that the plastic melt can fill the mold cavity smoothly. After filling, the mold is cooled to a lower temperature to cool the plastic melt in the mold cavity quickly, so as to avoid the adverse effect of high mold temperature on the injection production efficiency in the filling effectively [52]. Compared with the hot runner technology, the rapid heating circulation technology mainly focuses on the heating and cooling of the cavity and core, while the hot runner technology is to heat the runner, and the heating of the mold should be avoided. Therefore, the accurate control and rapid response when using rapid heating cycle technology for injection molding, the process usually needs a more complex temperature control system, as shown in Fig. 2.33.

② Process characteristics of rapid heating cycle injection molding [54]

According to the principle of rapid thermal cycle injection molding, we need to heat and cool the mold rapidly, which is the core of the process. For the rapid cooling of the die, the most common method is to pass the low-temperature cooling medium into the inner pipe of the mold at high speed, and cool the mold by convection heat transfer. Practice shows that this method is simple and easy to operate, and has high cooling efficiency. Compared with the rapid cooling of the mold, the rapid heating of the mold is much more difficult. In order to achieve rapid heating of mold, researchers



1-Injection machine; 2-Mold; 3-Electric heater; 4- Platinum resistance temperature sensor;
5- Cooling water inlet valve; 6- Cooling water circulator; 7-Air compressor; 8-Air valve; 9-
PLC controller; 10- Human-computer interaction interface

Fig. 2.33 Electric heating rapid heating cycle injection control system [53]

at home and abroad have carried out a lot of research work. Here, several common rapid heating methods are introduced.

- a. Electric heating. Electric heating is the method of using resistance to heat the mold, commonly used are electric heating tube, electric heating plate, electric heating coil and so on. The heating rate of resistance element is high, which is $1\sim3\text{ }^{\circ}\text{C/s}$, and the temperature control range can be greater than $350\text{ }^{\circ}\text{C}$. In the process of injection molding, the resistance element is used to heat the mold cavity and core rapidly to near or higher than the glass transition temperature of polymer, and keep the mold at a constant temperature.

The electric heating method has high efficiency and a relatively simple control method, the product's quality will be improved, also the production cycle will be shortened, but the electric heating system is directly installed in the mold which make the mold structure is more complex (Fig. 2.34) and needs a high cost and special design, and the heating is transmitted to the mold through heat radiation, resulting in large heat loss along the way.

- b. Steam heating. Steam heating is a process in which high temperature steam and condensed water are alternately introduced into the internal pipeline of the mold by using the mold temperature control device to realize the rapid heating and cooling of the mold. The steam heating system can make the mold surface temperature up to $160\text{ }^{\circ}\text{C}$. But steam heating, heating time is longer.

In order to ensure the uniformity and rapid change of mold temperature, a reasonable pipe must be set inside the mold to ensure the rapid heating and cooling. The steam heated mold is more complex, so it is necessary to arrange the pipe at

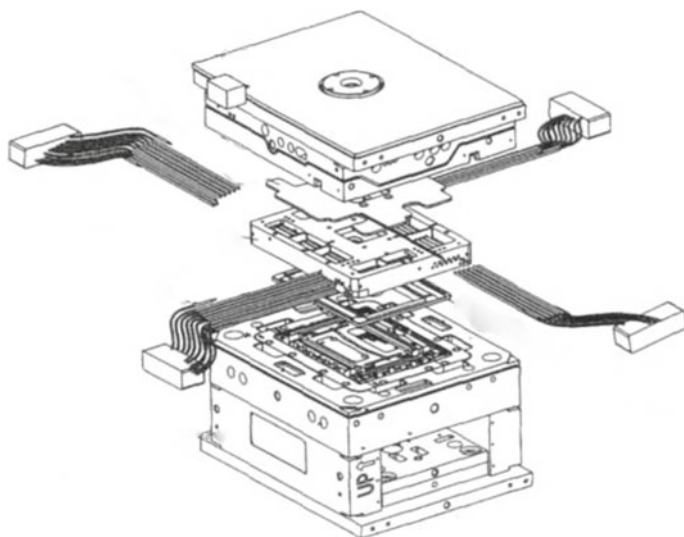


Fig. 2.34 Electric heating rapid heating cycle injection mold [55]

a constant distance from the mold surface through hierarchical structure or other special methods to meet the above requirements.

- c. Electromagnetic induction heating. Electromagnetic induction heating is also one of the most mature heating methods, it is based on Faraday electromagnetic induction principle to heat the mold. Electromagnetic induction heating can only act upon from the surface to skin depth of the mold. It has a small volume and a fast heating speed. The heating speed of the system developed by Chung Yuan Christian University can exceed 40 °C/s.

There is no heat transfer medium between the electromagnetic induction system and the mold, so it has the advantages of fast heating speed and short processing cycle. The skin effect can only heat the surface of the mold to save energy. It can also heat the special parts of the mold, such as the micro structure or the parts that may have weld lines. As a heating source, electromagnetic induction is more efficient than electric heating and steam heating, which saves energy consumption in the heating process and has the advantages of flexibility, convenience and safety.

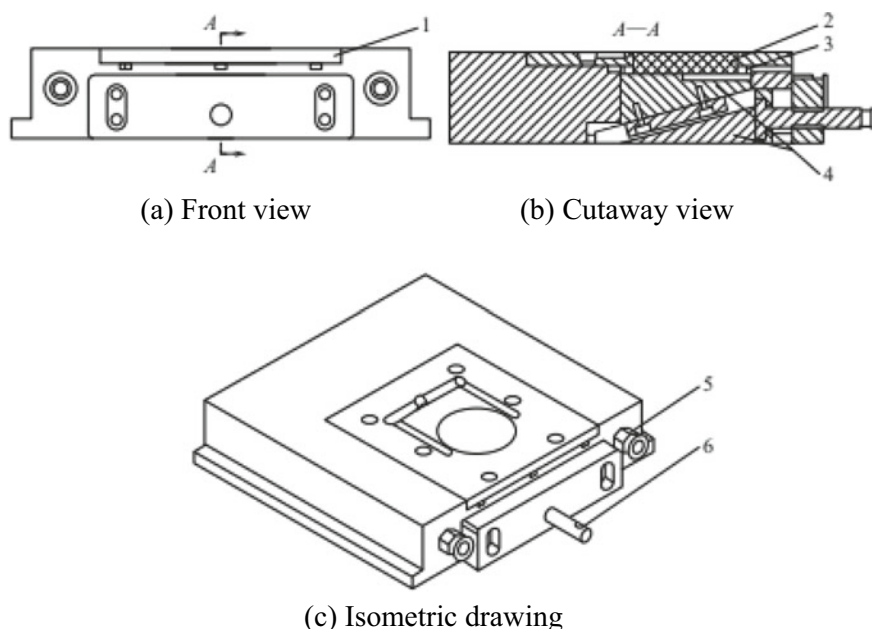
- d. Auxiliary heating of graphene coating [56]. The auxiliary heating of graphene coating is a heating method proposed by En-learn Laboratory of Beijing University of Chemical Technology. Continuous and compact chemical bonded graphene nano coating was prepared on the surface of mold cavity of silicon material. Because the coating keeps the physical characteristics of high conductivity, high heat conduction and super smooth of grapheme, the surface temperature of the cavity can be rapidly increased to the glass transition temperature of polymer materials under the driving of external power supply, so as to realize the rapid thermal cycle of injection molding process.

The structure of the mold used in this process is shown in Fig. 2.35, and use this mold to do injection experiment. The results show that the auxiliary heating of graphene coating can effectively reduce or even eliminate the weld lines, further reduce the surface defects of multi gate products, improve the surface quality of products, and significantly improve the ability of copying the cavity structure of products under low injection speed and pressure, and can shape the micro-nano structure of products. This technology has a broad prospect in the field of forming ultra-thin and micro nano complex structure of precision injection parts.

(9) Photopolymer injection molding [57, 58]

① Photopolymer

Photopolymer Injection Molding is a process for injection curing of photopolymer materials. The Photopolymer refers to a kind of resin material which can be cured by using the ability of light to excite the molecular active group. It mainly includes the pre-polymer acting as the main polymer component, adjusting the viscosity of the system and acting as the active diluent of the secondary polymer component, and



1-Gate plate; 2-Silicon core plated with grapheme; 3-Cooling plate(copper); 4-Adjusting wedge;
5-Cooling water connector; 6-Adjusting screw

Fig. 2.35 Rapid thermal cycling injection molding experimental mold

the photoinitiator providing free radicals or cations for the reaction. Photopolymer have the following characteristics:

- Photopolymer is a liquid material. It does not need heating and plasticization during its forming process. It not only saves a lot of energy and time, but also avoids the defects of uneven properties and degradation of some materials caused by temperature gradient.
- Polymerization occurs only when photopolymer resin is exposed to light, which avoid the accumulation of internal stress due to local fixation during flow and achieve true conformal curing.
- Solvents participate in the curing reaction at the same time in the photopolymer reaction, which greatly reduces the residue of toxic substances.

② Process and equipment for photopolymer injection molding

Photopolymer reactions are being used more and more widely in materials molding, such as 3D printing and Photopolymer molding. On this basis, using the light curing properties of photopolymer materials, the injection molding process of photopolymer

materials was developed by En-learn Laboratory of Beijing University of Chemical Technology. The basic injection process is as follows:

- a. Making the photopolymer resin inject into the transparent cavity at high speed and fully compressed.
- b. Under higher pressure, apply light to the resin and maintain the pressure during the curing process of the resin.
- c. After stopping the pressure supply, continue to light for a period of time to harden the resin and take out the product.

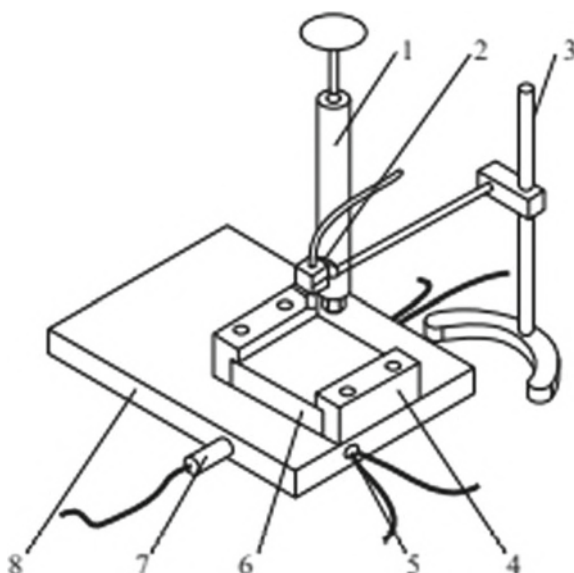
Because the photopolymer material is liquid at room temperature, its curing process depends on light, so its injection molding equipment is very different from the conventional injection molding machine, mainly reflected as the following aspects:

- a. Injection device. Because the photopolymer material is in liquid state during injection, the screw is not needed for melting, and the plunger is used for transportation.
- b. Mold. The mold is the place where the photopolymer materials are solidified and formed. Due to the need of light, special design is needed, which make it more complex. As shown in Fig. 2.36, the micro structure photopolymer molding equipment designed by L Chang et al. Is composed of mold base plate, a replaceable mold core with micro structure, transparent quartz glass template, piston injection device and ultraviolet light source. The bottom plate of the mold is placed horizontally, the transparent template is covered above the template and fixed with bolts, and the light source is placed above the transparent template. The piston injection device consists of a plunger and a cylinder, which are vertically inserted into the mold. The pistons are pushed by weights of different weights to realize the control of different molding pressures.

③ Advantages and applications of photopolymer injection molding

The advantages of photopolymer injection molding are mainly reflected in the following aspects:

- a. There is no plasticizing process. The photopolymer resin is liquid at room temperature, so it is not limited by screw size, and there is no problem of uneven plasticization of plunger injection molding machine. It can be very convenient to realize the miniaturization of the equipment, and the structure of the instrument can be very simple.
- b. The viscosity of the photopolymer resin is very low, and the flow characteristics will not be changed due to the cooling during the filling process. Therefore, the flow in the mold is not limited. Theoretically, the depth width ratio of the photopolymer resin can reach infinite length. At the same time, its excellent flow characteristics are also conducive to the replication of the microstructure.
- c. According to the needs of molding, photopolymer injection molding can apply light in the mold in stages to realize the controllable curing.



1-Injection device; 2- Ultraviolet source; 3-Adjusting stand; 4- Bolt fixing device; 5-Heater; 6- Transparent template(quartz); 7- Temperature sensor; 8- Base plate of mold

Fig. 2.36 Photopolymer equipment

In conclusion, photopolymer injection molding technology shows a good development prospect in the field of micro-nano products processing. Photopolymer injection machine can ensure a good filling effect of products, especially suitable for injection molding of precision parts with high aspect ratio and micro nano structure, such as microfluidic chips, micro-nano light guide elements, micro actuators and other precision products.

(10) Nano molding technology

In the electronic industry, the combination of hardware and plastic is becoming more and more popular. Due to the excellent performance of both aesthetics and electromagnetic shielding, designers tend to use metal as shell and chassis materials for portable electronic devices (such as mobile phones, tablets and laptops). However, metals do not have some of the properties of plastics, such as transparency, colorability, low cost and reprocessability. Therefore, the combination design of metal and plastic is very important.

① Principle of nano injection molding

Nano injection molding is a combination technology of metal and plastic. Nano injection molding is the best way to solve the problem that the outer shell needs

metal performance, complex structure and light weight. It is used to replace plastic embedded metal injection, zinc aluminum and magnesium aluminum die castings. Nano injection molding can provide a gold plastic integrated product with price competition, high performance and lightweight.

In recent decades, nano injection molding (NMT) technology has been widely used to replace the traditional metal insertion molding method. The specific method is that the metal surface is pretreated to produce nano pores, and then the plastic parts infiltrate into the metal directly to produce a firm interface bonding. Because this single-step injection molding process can easily form a combination, the cost of manufacturing metal parts is reduced compared with the traditional method. The process of nano injection molding is shown in Fig. 2.37.

In the whole process of nano injection molding, t (Taisei) treatment is a very important process. As shown in Fig. 2.38, there are mainly four steps as follows: forming nano layer by alkali washing; Then, acid soaking was carried out to promote the evolution of the nano layer; Then T reagent was used to prepare for the reaction with resin during injection; Finally, use water to wash.

The reagents used in T treatment are called T reagent, which have three main functions: to create nanopores on the metal oxide layer; Filling nanopores to remove air; When injected, it reacts with engineering plastics. As shown in Fig. 2.39, even if it is possible to produce metal substrate with nano holes on the surface, the plastic cannot shoot into such small nano holes (unable to exhaust and may produce wind entrapment), so it has no binding ability at all, and the plastic mechanism falls off immediately. After the metal substrate is etched by T treatment reagent, the plastic is injected to produce chemical reaction, and the two are exchanged and fused. The nano

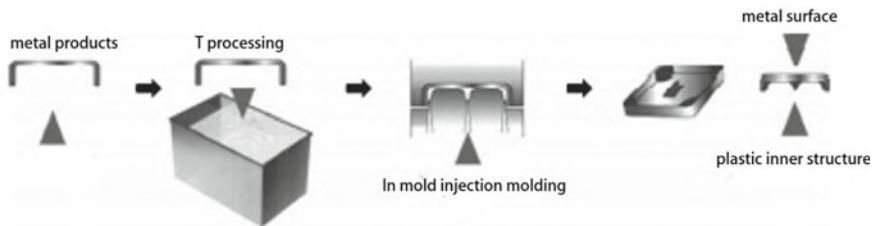


Fig. 2.37 The process of nano injection molding

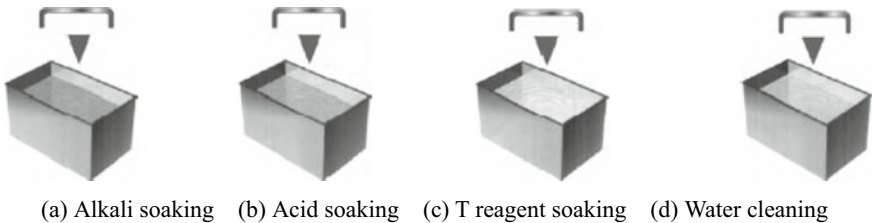
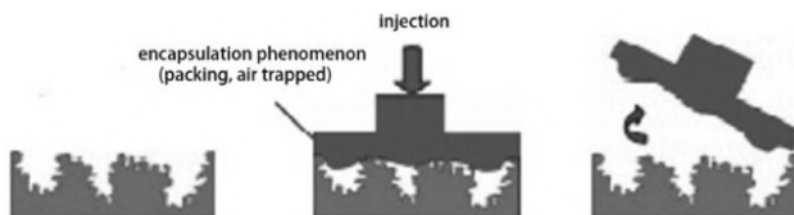


Fig. 2.38 The process of T (Taisei) treatment



(a) Adhesion of metal substrate with nano holes on its surface to plastics



(b) Adhesion between metal substrate and plastic after acid etching with T agent

Fig. 2.39 Anchor bolt effect caused by reaction of engineering plastics and T agent

pores are quickly “occupied” by the two kinds of reactants, and the plastic structure immediately produces anchor bolt effect to fasten on the metal (see Fig. 2.39).

② Resin for nano injection

Resin and metal for nano injection must be compatible, and can carry out NMT process, many thermoplastic resins can meet the conditions, but because the metal must be colored, the secondary processing is often carried out after molding, we call it anodizing. During anodizing, the material will be exposed to acidic solution for many times to achieve the required color, so chemical resistance, especially acid resistance, becomes a requirement of material selection, which limits some polymers, such as polyamide. In addition, the resin can be reinforced with glass fiber to reduce shrinkage and improve mechanical properties. The coefficient of linear expansion of the plastic compound also needs to match the metal, otherwise, excessive internal stress may lead to surface cracks, and reducing the bonding effect.

Due to these factors and the requirements of colorability, low cost and metal plastic affinity, polyphenylene sulfide (PPS) and polybutylene terephthalate (PBT) have become the mainstream choice, which have good chemical resistance and mixing performance. PPS and high crystalline resin can form a good combination in the NMT process, but the processability is poor and the aesthetic performance is low (including limited color space, rough surface, difficult to paint/varnish and poor weather resistance). PBT of semi crystalline resin has good processability, easy coloring, high weather resistance and halogen-free. It also has high rigidity, tensile strength, wear resistance and low friction performance. However, PBT has relatively

low impact resistance and shrinkage, which can be improved by preparation and proper treatment.

At present, aluminum and aluminum alloy, magnesium and magnesium alloy, stainless steel and so on have been mass produced and can be used; The plastic materials that can be used are PPS, PBT, PA (nylon), etc. In order to prevent the expansion and contraction speed of plastics from being higher than that of metals, some fibers, such as glass fiber and carbon fiber, will be added to make the thermal expansion and contraction of plastics similar to that of metals.

③ Advantages and disadvantages of nano injection

Nano injection technology has many advantages, such as reducing the overall thickness and height of the product, reducing the overall weight of the product, excellent mechanical structure of strength, high processing speed and output of metal substrate (stamping forming), more choice of appearance decoration methods, higher reliability of combination (compared with gluing technology), etc.

Of course, its application is limited due to some reasons, such as the high cost of large parts, the limitation of five metal alloys (iron, aluminum, magnesium, titanium and copper alloys), the limitation of three plastic materials (PPS, PBT, PA/PPA), and the influence of thermal expansion deformation between metal and plastic.

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Chapter 3

Polymeric 3D Printers



3D printers are based on digital model files, using special wax materials, powdered metals or plastics and other adhesive materials to create three-dimensional objects by printing layers of adhesive materials. The principle of a 3D printer is to gradually stack products according to the data and commands in the digital model file.

The biggest difference between 3D printers and traditional printers is that the “ink” used by 3D printers is a tangible raw material. There are many forms of stacking thin layers, and there are various types of media that can be used for printing, such as plastic, metal, ceramic, and rubber. Some printers can also combine different media to create physical objects with multiple properties. According to the technical method used, 3D printers mainly include fused deposition modeling (FDM), selective laser sintering (SLS), stereo lithography appearance (SLA), and laminated object manufacturing (LOM), 3D printing(3DP), etc. According to the classification of the processing range, 3D printers are mainly divided into industrial grade and desktop grade. Industrial-grade equipment generally uses technologies such as SLS and 3DP. It can process large-size products and is expensive. It is mainly used in automobiles, national defense, aerospace and other fields. The size of products processed by desktop-grade equipment is generally small, and it is mainly used in product development and model making.

The main features of 3D printers are as follows:

- ① For traditional manufacturing technology, component design is limited by the production process, and it is necessary to consider the feasibility of the machine itself to achieve processing. However, the emergence of 3D printers will subvert this production idea, which makes companies no longer consider production process issues when producing parts, because 3D printers can meet the materialization of any complex shape design.
- ② 3D printers can generate objects of any shape directly from computer data, without molds or mechanical processing, which greatly shortens the product development cycle and improves productivity. Although it still needs to be

improved, the market potential of 3D printing technology is huge, and it is bound to become one of the many breakthrough technologies in the future manufacturing industry.

- ③ Compared with traditional processing machinery, 3D printers are much lighter and cause less pollution to the environment. It is precisely because of its advantages that it is easier to enter people's daily lives. Today we can buy this type of printer in some electronics stores, and the factory is also selling it directly.

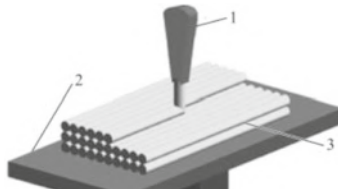
3.1 Common Techniques for Polymer 3D Printing

Polymer 3D printing technology can be divided into filament fused deposition modeling (FDM), selective laser sintering (SLS), stereo lithography appearance (SLA), and laminated object manufacturing (LOM), 3D printing (3DP), micro-droplet jetting (MDJ), etc.

(1) Fused deposition modeling (FDM)

Due to its simple operation, fused deposition molding has become the most commonly used molding technology in desktop 3D printing equipment [1]. Fused deposition modeling 3D printer consists of a fuse extrusion device and a three-dimensional motion platform. Its molding method is as follows: the thermoplastic filament is heated and melted at the nozzle, and the motor drives the extrusion nozzle to extrude according to the deposition path planned by the model file. At the same time, the stepping motor drives the gear to squeeze the filament into the melting cavity according to the predetermined pulse. The extruded melt is bonded, cooled and solidified on the substrate, and the layers are stacked to form a three-dimensional plastic product, as shown in Fig. 3.1.

The materials used for FDM are generally thermoplastic materials, silk materials with melting points ranging from 100 to 300 °C, such as PLA, ABS, nylon, etc. Among them, because ABS has the advantages of low molding shrinkage and high strength, the molded parts have high strength, which can be directly used for trial assembly, test evaluation and bidding, and can also be used to make master molds for rapid and economical molds.



1-fuse extruding device; 2-three-dimensional motion platform; 3-fuse stacking

Fig. 3.1 Schematic diagram of the principle of fused deposition modeling

FDM process needs to add support material when printing hollow parts or cantilever parts. When the support material is the same material, only one nozzle is needed. That is, during the molding process, the operating speed of the nozzle can be controlled by the control system to make the support material looser, so as to achieve the purpose of facilitating peeling and accelerating the molding speed. However, because the model material and the support material are the same material and the same color, even if the density is different, it is difficult to identify and peel off at the boundary. And when the support material is peeled off, it is easy to damage the molded part. With the form of dual nozzles, it can be used not only to spray model materials, but also to spray support materials. Using the different characteristics and colors of the two materials, physical or chemical methods can be used to remove the support after the production is completed. If the water-soluble material is used as the support and the non-water-soluble material is used as the model, the molded part can be directly put into the water after the molding is completed to dissolve the supporting material, and the final prototype can be obtained. Or use low melting point materials as support and high melting point materials as models. After molding, you can choose to heat at the melting point of low melting point materials to melt and remove the support materials to obtain the final prototype [2].

Compared with other 3D printing technologies, Fused Deposition Modeling (FDM) is the only additive manufacturing method that uses industrial-grade thermoplastics as molding materials. The printed products have better heat resistance, corrosion resistance, and antibacterial properties. At the same time, the internal mechanical stress of the product is relatively small. In addition, the FDM-based 3D printing technology does not require a laser, which not only has the advantages of convenient maintenance and material saving, but also has low operating costs and high material utilization. Due to its large variety, high strength and high precision of molded parts, it is increasingly used to manufacture conceptual models, functional prototypes, and even directly manufacture parts and production tool molding materials [3]. However, FDM technology also has some shortcomings. The process needs to scan and coat the entire cross section, so the molding time is longer. Because the raw material is required to be wire, the cost of raw materials has risen. Sometimes it is necessary to design and manufacture supporting structures.

The development process of FDM technology is as follows. In 1988, Scott Crump invented Fused Deposition Modeling (FDM) and established Stratasys. In 1992, Stratasys introduced the first 3D printer based on FDM technology, marking the commercialization of FDM technology. The printer is compact in structure, easy to install, simple to operate, convenient and reliable, and can be placed on the desk for physical printing. In 2002, Stratasys developed the Dimension series of desktop 3D printers which are also based on FDM technology. This printer uses ABS plastic as the molding material and is relatively inexpensive [4]. In 2012, Stratasys released an ultra-large rapid prototyping system with a molding size of $914.4 \text{ mm} \times 696 \text{ mm} \times 914.4 \text{ mm}$. Its printing error was an increase of $0.0015 \sim 0.089 \text{ mm}$ per millimeter. The minimum printing layer thickness was only 0.178 mm . In 2016, Yifan et al. [5] used polylactic acid (PLA) as a raw material and used a fused deposition modeling 3D printer to make a medical solid model of the human pelvis and part of the spine. The

finished product can meet medical requirements. In the same year, Stratasys introduced four enhancements for FDM 3D printers, including Sacrificial Tooling (sacrificial tooling process) solution for processing complex hollow structure composite parts, Fortus 900mc acceleration package for faster manufacturing of large parts and molds, the first ULTEM material that meets all aerospace material traceability standards and the high-strength PC-ABS material used on more Stratasys 3D printers. The research of FDM printing equipment mainly focuses on reducing equipment cost and improving processing accuracy and efficiency.

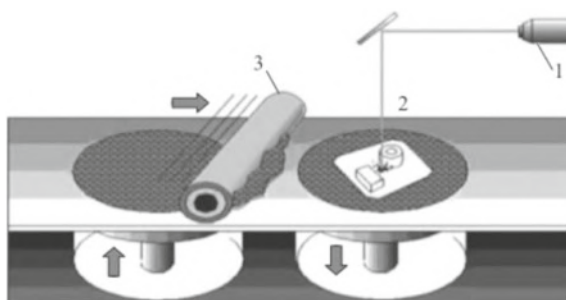
(2) Selective laser sintering (SLS)

Selective laser sintering (SLS) is a rapid prototyping technology. Specifically, it is based on the principle of discrete-stacking, using computer-aided design and manufacturing, to selectively sinter the material powder layer by layer through laser, and then stack it layer by layer to form a three-dimensional solid part.

Selective laser sintering 3D printer is mainly composed of laser, roller, powder pool, forming pool and so on. First, the powder is uniformly pushed into the forming tank through the roller, and then the laser irradiates the sintered powder consumable according to the scanning path of the three-dimensional model slice, and the powder in the selected path is melted and bonded to form a welding surface. Then the roller pushes the second layer of powder to complete the sintering of the second layer, and bond with the first layer of welding surface under high temperature, layer by layer sintering and superimposition, and finally form a three-dimensional solid model, as shown in Fig. 3.2.

Compared with other rapid prototyping methods, the most prominent advantage of SLS is that it uses a wide range of molding materials. Theoretically, any powder material that can form interatomic bonds after heating can be used as a molding material for SLS. At present, the materials that can be successfully processed by SLS are paraffin, polymer, metal, ceramic powder and their composite powder materials [6]. Therefore, selective laser sintering can produce metal products such as iron, nickel, titanium, aluminum, and plastics, ceramics, paraffin and other products. The molding does not require additional support, because the unmolded powder between the layers can be used as a support material.

Fig. 3.2 Schematic diagram of the principle of selective laser sintering



1-laser; 2-forming pool; 3-roller

Selective laser sintering (SLS) [7] has the following characteristics. ① Short molding cycle and low production cost. ② A wide range of applicable molding materials, including paraffin wax, metal powder, plastics, ceramics and their composite powders, etc. ③ The shape of the molded part is not limited, and has nothing to do with the complexity of the part. ④ It has a wide range of applications. Due to the flexibility of its molded parts, it is suitable for many fields, such as casting cores, mold master molds, prototype design verification, etc. ⑤ It can be combined with traditional process methods to realize functions such as rapid casting, rapid mold manufacturing, and output of small batch parts.

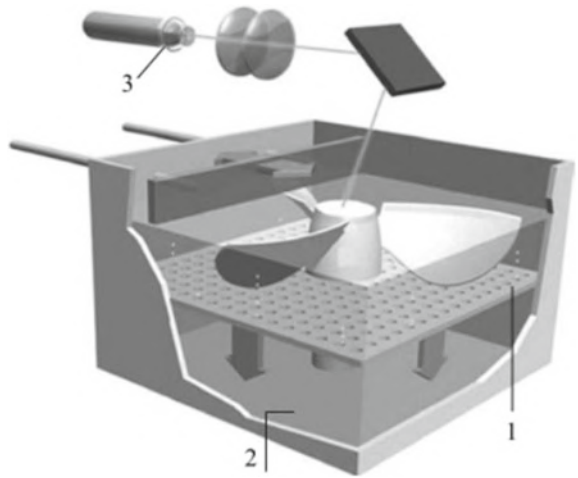
However, selective laser sintering molding technology also has some disadvantages. ① The inside of the part is loose and porous, the surface roughness is large, and the mechanical properties are not high. ② The quality of the part mainly depends on the nature of the powder itself, and it is not easy to improve. ③ The maximum size of manufacturable parts is limited. ④ The molding consumes a lot of energy and the post-processing procedures are complicated.

The development process of SLS technology is as follows. In 1986, Deckard, a graduate student of the University of Texas in the United States, first proposed the idea of selective laser sintering and obtained the first SLS technology patent in 1989. In terms of SLS research, American DTM company has a number of patents. In 1992, the company launched the Sinterstation 2000 series of commercial SLS molding machines, and in 1996 it introduced the improved SLS molding machine Sinterstation 2500, and in 1998 it launched the Sinterstation 2500plus. At the same time, a variety of sintered materials have been developed, which can be directly used to make wax molds, plastics, ceramics and metal parts. The German EOS company successively launched three series of SLS molding machines in 1994, namely EOSINT P, EOSINT M and EOSINT S. The domestic research on SLS technology started in 1994. Beijing Longyuan Company successfully developed the first domestically-made laser rapid prototyping machine in early 1995. Subsequently, Huazhong University of Science and Technology also produced the HRPS series of SLS molding machines. At present, many domestic enterprises and universities are still studying this technology.

(3) Stereo lithography appearance (SLA)

Stereo lithography appearance (SLA) uses liquid photosensitive resin as raw material. It is a technology based on the principle of layered manufacturing. Its working principle is similar to that of selective laser sintering, as shown in Fig. 3.3. Under computer control, ultraviolet light or laser of a specific wavelength is scanned point by point along each layered section of the computer model. The liquid resin in the scanning area is cured by photopolymerization, thereby forming a thin layer of the part. After one layer is cured, the workbench moves in the vertical direction so that the surface of the cured resin is covered with a new thin layer of resin, which is stacked layer by layer, and finally a physical prototype is formed, the support is removed, and the post-processing is carried out. And then obtain the required physical prototype. The difference between SLA and SLS is that the molding light source of SLA technology is an ultraviolet generator, and the consumables used in SLA are

Fig. 3.3 Schematic diagram of the principle of stereo lithography appearance



1-lifting platform; 2-photosensitive resin; 3-ultraviolet lamp

photosensitive resin liquid. A photoinitiator is added to the photosensitive resin, and the polymerization reaction occurs under the irradiation of ultraviolet rays, and the resin is cured and formed [8]. SLA molded products have high precision, generally reaching below 0.1 mm, and the technology is mature and widely used. However, the light-curing molding process needs to be realized in a resin tank. After printing, the resin adhered to the surface needs to be cleaned with alcohol. Because the resin has a pungent odor, the printing environment is relatively harsh.

The main components of the liquid photosensitive resin are oligomers, photoinitiators and diluents. When the photosensitive resin is irradiated with ultraviolet light or laser of a specific wavelength, the photoinitiator will absorb energy and generate free radicals or cations. Free radicals or cations in turn activate monomers and oligomers. As a result, a cross-linking reaction occurs and a polymer cured product is further produced. The reaction mechanism of photosensitive resin is shown in Fig. 3.4.

Stereo lithography appearance is a relatively high-precision rapid processing technology, which has the following advantages. ① The molding process is highly automated. The SLA system is very stable. After the processing starts, the molding process can be fully automated until the prototype is completed. ② High dimensional accuracy. The dimensional accuracy of the SLA prototype can reach ± 0.1 mm (within 100 mm). ③ The surface quality is excellent. Although steps may appear on the sides and curved surfaces when each layer is cured, the glass-like effect can still be

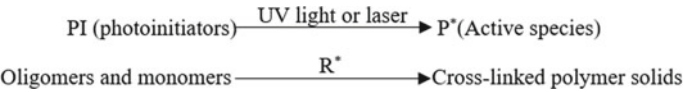


Fig. 3.4 Schematic diagram of photosensitive resin reaction mechanism

obtained on the upper surface. ④ It can make very complex models. ⑤ It can directly produce lost foam with a hollow structure for investment casting [9].

Compared with several other rapid prototyping processes, SLA also has many disadvantages. ① The molding process is accompanied by physical and chemical changes. Therefore, the parts are easier to warp and deform, and support needs to be added. ② Equipment operation and maintenance costs are relatively high. Liquid photosensitive resin materials and lasers are both expensive. ③ There are fewer types of materials that can be used. The currently available materials are mainly liquid photosensitive resins. And in most cases, it is generally brittle and easy to break, which is inconvenient for machining, and cannot be tested for resistance and heat. ④ The product requires secondary curing. In many cases, the resin is not fully cured in the prototype after light curing by the rapid prototyping system, so a secondary curing is required.

According to the different molding processing systems, SLA 3D printers are mainly divided into high-end light-curing rapid prototyping machines for the development of molding industrial products and low-end light-curing rapid prototyping machines for molding three-dimensional models. 3D Systems in the United States, EOS in Germany, CMET, Seiki and Mitsui Zosen in Japan are all studying stereo lithography appearance. In 1999, 3D Systems launched the SLA-7000 model with a scanning speed of 9.52 m/s and a minimum layer thickness of 0.025 mm. Japan's AUTOSTRADE company uses a semiconductor laser as a light source with a wavelength of about 680 nm, and has developed a visible light resin for this wavelength. Xi'an Jiaotong University has also conducted in-depth research on SLA molding. And introduced LPS series and CPS series rapid prototyping machines. And also developed a photosensitive resin with superior performance and low cost [10].

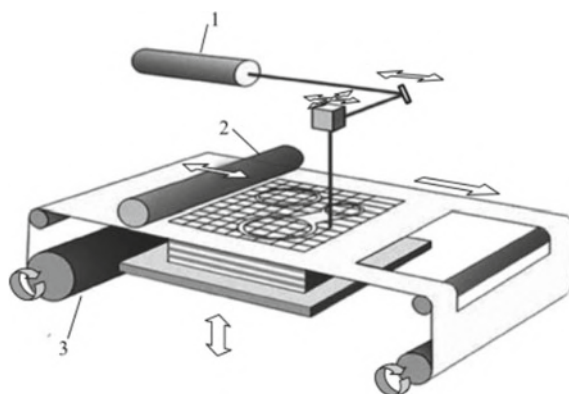
With the development of technology in recent years, the ultraviolet generator has gradually evolved from a point light source to a surface light source [11]. Printing by imaging and projection can produce products of the same size as a large LCD screen. By performing surface curing, the molding efficiency can be greatly improved.

(4) Laminated object manufacturing (LOM)

Laminated object manufacturing (LOM), also known as layered solid manufacturing technology. The basic principle of LOM is shown in Fig. 3.5. The hot melt adhesive is applied to the thin layer of material. This thin layer material can be paper, plastic film or composite material. Then, under the pressure and heat transfer of the hot-pressing roller, the hot melt adhesive is melted to bond with the thin layer. Then, the laser located above cuts out the inner and outer contours of the cross-sectional layer according to the data obtained by computer layering. Each time the laser processes a layer, the worktable is lowered a certain distance, and then a new thin layer is superimposed on it. Repeatedly, layer by layer into a three-dimensional solid. After post-processing, the unbonded diaphragm consumables around the model are peeled off to obtain the required three-dimensional products [12].

Laminated object manufacturing mainly uses paper, polyvinyl chloride, and polyethylene film as raw materials. In addition, consumables such as metals, ceramics, and wood-plastic [13] also have related research on the use of laminated

Fig. 3.5 Schematic diagram of the principle of laminated object manufacturing



1-laser; 2-heat pressing roller; 3-drive wheel

object manufacturing. The LOM molding process is processed by contour cutting, so the molding efficiency is high. However, there are shortcomings such as narrow selection of consumables, low mechanical strength, and waste of raw materials.

For the molding material used in LOM, it has the following requirements. ① It should have good moisture resistance. Ensure that the raw materials will not absorb water due to a long time. So as to ensure that there will be no deformation and weak bonding due to the loss of moisture during the hot pressing process. ② It should have good wettability to ensure good coating performance. ③ It should have a certain tensile strength to ensure that it will not be broken during processing. ④ The shrinkage of the molding material should be small to ensure that it will not be deformed due to partial water loss during the hot pressing process. ⑤ The peeling performance of the molding material is required to be good. ⑥ Easy to sand, smooth surface.

After the prototype is laminated, it is necessary to apply a certain pressure to the laminated block, and then remove the pressure after it is sufficiently cooled, so as to control the thermal warpage deformation of the laminated block when it is cooled. It is necessary to peel off the waste material after sufficient cooling, so that the waste material can support the workpiece, and reduce the large deformation caused by the insufficient local rigidity of the workpiece and the complex structure. In order to prevent the work piece from absorbing moisture and swelling, the surface treatment of the work piece that has just been stripped of waste should be carried out in time. The surface treatment method is mainly to coat reinforcing agents (such as super glue, epoxy paint or polyurethane paint, etc.), which helps to increase the strength and moisture resistance of the parts.

Compared with other rapid prototyping technologies, laminated object manufacturing has the following advantages. ① The production precision is high. Under the action of the hot-pressing roller, only the surface layer of the thin layer material undergoes a solid to molten state transformation, while the base layer of the thin material remains unchanged. Therefore, the warping deformation caused is small,

and the production accuracy is correspondingly improved. ② No design support is required when LOM technology is formed. And the material price is low, the molding speed is fast, and the production cost is reduced. ③ Easy to manufacture large parts. The process only needs to cut the contour of the part section on the sheet, instead of scanning the entire section, so the speed of forming thick-walled parts is fast and it is easy to manufacture large parts [14].

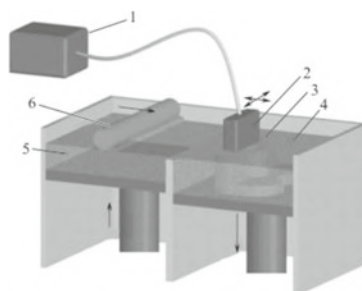
The disadvantages of laminated object manufacturing are as follows. ① In the process of manufacturing according to the contour of the product, the utilization rate of the thin layer material is low, and the waste material cannot be reused. ② If thin-walled products are formed, their tensile strength and other properties are relatively poor. ③ The surface quality of the molded part is poor and may require secondary processing. ④ The molded parts are easy to absorb moisture and deform, so the surface should be treated with moisture-proof in time.

At present, foreign Helisys, Kinergy, Singapore, Kira, etc. are all studying the LOM process, and these companies have their own molding equipment. Domestically, Tsinghua University and Huazhong University of Science and Technology both have research in this direction. The main products of Huazhong University of Science and Technology are HRP-IIB and HRP-IIIA. A 50W CO₂ gas laser is used. The molding space is 450 mm × 350 mm × 350 mm and 600 mm × 400 mm × 500 mm respectively. The thickness of the laminate is 0.08~0.15 mm. Has a high-cost performance. Now, it is possible to use LOM technology to form metal sheet parts samples, which is also a main development direction of laminated object manufacturing.

(5) 3D printing (3DP)

3D printing (3DP) process is basically similar to the selective laser sintering molding process. Both use powder as the basic molding unit, and the process flow is basically similar, as shown in Fig. 3.6. The difference is that selective laser sintering molding uses laser welding powder to form a body, while 3D printing molding uses a nozzle to spray adhesive to bond the powder, similar to the “ink” ejected in the printing process [15]. The consumables used by 3DP include metals, plastics and inorganic powders. After printing is completed, heat treatment is generally carried out to enhance the mechanical strength of the product.

3D printing (3DP) has the advantages of saving raw materials, microscopic molding, and environmental protection. In the molding process, the nozzle sprays the bonding material or other molding materials, and forms the parts through cooling or light curing. The time required to produce a part is much lower than other molding processes. Three-dimensional printing technology can use a wide range of materials. Products with attributes such as plastics and ceramics can be made, and conceptual models can also be made. It plays an important role in the direct rapid prototyping of metal parts, the molding and manufacturing of rapid abrasive tools, and the rapid repair of equipment [16]. This process is widely used in the 3D printing foundry industry, and is mainly used to prepare sand molds [17]. Compared with the original mold processing method, it has the advantages of faster molding time and lower cost.



1-adhesive box; 2-sprinkler; 3-bonded part; 4-unbonded part; 5-powder; 6-roller

Fig. 3.6 Schematic diagram of the principle of 3D printing

The development history of 3D printing technology is as follows. In 1993, Professor Emanuel Sachs of the Massachusetts Institute of Technology in the United States invented the 3D printing process. Manufacturers using 3DP technology are mainly Zcorporation, EX-ONE, etc. The 3DP equipment is mainly Zprinter and R series 3D printers. This type of 3D printer can use many materials, including plaster, plastic, ceramics, and metal. And it can also print color parts, the powder that is not bonded during the molding process plays a supporting role, and it can form parts with complex internal shapes.

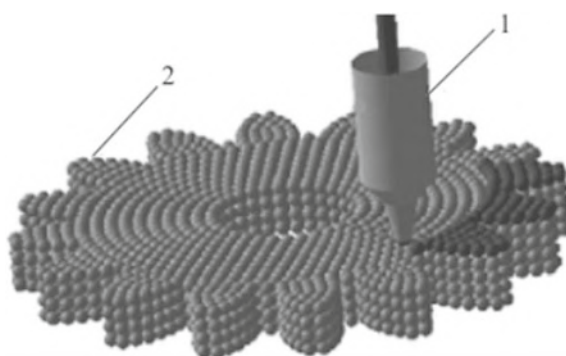
(6) Micro-droplet jetting (MDJ)

The micro-droplet jetting (MDJ) uses different driving forces to drive the solution consumables to be ejected from the nozzle onto the substrate in the form of tiny droplets. The tiny droplets form an array of droplets along the jet trajectory planned in the digital software, which are deposited and sintered layer by layer, and finally form a three-dimensional model [18], as shown in Fig. 3.7. “Tiny droplets” refer to controllable morphology, and the smallest droplet volume can reach the order of microliters or milliliters. At present, the commonly used inkjet printers use droplet injection molding technology to achieve on-demand deposition on two-dimensional paper. And through the three-dimensional solid accumulation of droplets, the application in 3D printed products can be realized.

The consumables currently used in droplet injection molding include resin-based solutions [19], paraffin, and metals [20]. The main advantage of micro-droplet jetting is its high molding accuracy, and because of multi-jet printing, multi-material and multi-color composite products can be prepared.

The development history of micro-droplet jetting is as follows. In the nineteenth century, the physicist and polymath Lord William Kelvin applied for a patent on changing the direction of liquid droplets by electrostatic force. This should be the time when micro-droplet jetting was clearly defined [21]. Since there was no specific equipment for spraying droplets at that time, the micro-droplet jetting has not been paid attention to. Until the 1950s, Siemens used this technique to plot machine output trajectories. From 1960 to 1980, the micro-droplet jetting made a major breakthrough

Fig. 3.7 Schematic diagram of the principle of micro-droplet jetting



1-sprinkler; 2-stacked products

in computer image output, and it also made important developments in printer manufacturing technology, manufacturing cost and printer size [22]. Now the micro-droplet jetting has become a very common personal printing tool, but the main commercial application field of the micro-droplet jetting is still images and other traditional printing. In 1980, Canon developed the first thermal bubble inkjet printer Y-80, and then Hewlett-Packard also launched its own thermal bubble printer [23]. So far, micro-droplet jetting has begun the transition from continuous jetting technology to on-demand jetting technology. In 1989, Nordson ASYMTEK of the United States began to study micro-droplet jetting, mainly dedicated to the application of hot melt adhesives and microelectronic packaging technology. With the deepening of research on the application of micro-droplet jetting, it has been widely used in biomedicine, material molding, microelectronic packaging and genetic engineering.

3.2 Polymer Direct Melt 3D Printing Equipment

Conventional 3D printers have high requirements for printing consumables. It is necessary to add quantitative filling materials for co-mixing modification to improve the fluidity and shrinkage of consumables. For example, currently fused deposition modeling (FDM) printing materials commonly used mainly include PLA and ABS. Stereo lithography appearance requires photosensitive resin as printing materials, and the cost of consumables is relatively high. For fused deposition modeling 3D printers, because of the use of wire as consumables, it needs to be pre-prepared with an extruder. Compared with the molding equipment that directly uses standard plastics, the cost is higher. Take the commonly used ABS consumables as an example, the market purchase price is about 70 yuan/kg, while the price of pellets is about 12 yuan/kg, the contrast is obvious. In addition, the performance of consumables is reduced after the second thermal processing, which affects the performance of the product.

Due to the characteristics of fused deposition modeling consumables and process limitations, this technology, as a special method of polymer processing and molding, has many disadvantages compared with 3D copying technology (molding). However, there are obvious advantages in the preparation of small batches and personalized products. Therefore, some scholars have redesigned the fused deposition modeling technology and equipment to reduce the shortcomings of the existing fused deposition modeling process. The polymer direct melting 3D printing described in this section belongs to a type of micro-droplet jetting. It is to put polymer pellets directly into the screw plasticization system to melt and plasticize, and then flow out at a certain frequency through a switch-type nozzle. Stack molded products. There are two main types: one is the free former system introduced by the German Arburg company; the other is the melt differential 3D printer proposed by the author's team.

3.2.1 Free-Forming Machines

Arburg's freeformer system was launched for the first time at the K1013 International Chinaplas in Dusseldorf, Germany in October 2013 (Fig. 3.8). Its basic principle is to melt and plasticize solid pellets directly, and then stack the droplets under the action of piezoelectric actuators. This equipment has great advantages in terms of raw materials. According to Arburg, conventional injection molding materials can be used at a cost of 2 to 3 US dollars/kg, while other 3D printing equipment special materials need 100 to 300 US dollars/kg. At present, this equipment still has some problems, such as low molding rate, poor surface quality of parts, product strength is only 85% of the same injection molded product, and product ductility is only 90% of the same injection molded product.

The free former system is similar to the extrusion system. But instead of continuous extrusion, the thermoplastic is melted and plasticized, and the micro-droplets are accumulated at a relatively high frequency. The accumulation frequency at the product boundary is 60 Hz, and the accumulation frequency inside the product is 200 Hz. The free former system is equipped with droplet deposition nozzles, which are driven by linear motors for 3-axis or 5-axis linkage. And it is equipped with two blanking devices, which can perform 3D printing of two different materials.

3.2.2 Melt Differential 3D Printers

Similar to the Arburg's free former system, there is also the melt differential 3D printing technology proposed by the author based on the "calculus idea of advanced manufacturing of polymer materials" [24]. It also directly uses plastic pellets as raw materials, which broadens the selection of consumables. At the same time, it reduces the cost of consumables and has unique advantages in batch printing products and



Fig. 3.8 Arburg's free former system

processing large products. The working principle of melt differential 3D printing is shown in Fig. 3.9.

Melt differential 3D printing is a molding process based on the fused deposition molding method. The molding process includes three parts: consumable melting, on-demand extrusion, and accumulation molding. The basic principle is shown in Fig. 3.10. After the thermoplastic pellets are heated, melted and plasticized in the barrel, they are compressed by the screw and transported to the hot runner. The melt is evenly distributed into each valve cavity through the hot runner, and the valve needle is opened and closed under the action of external force, and the melt is extruded out of the nozzle as needed to form a melt “micro unit”. In addition to dividing the product electronic model by layer, it is also evenly divided into multiple filling areas in the same layer. During the stacking process, the melt “micro-units” fill the relevant areas as needed, and stack them layer by layer to finally form a three-dimensional product.

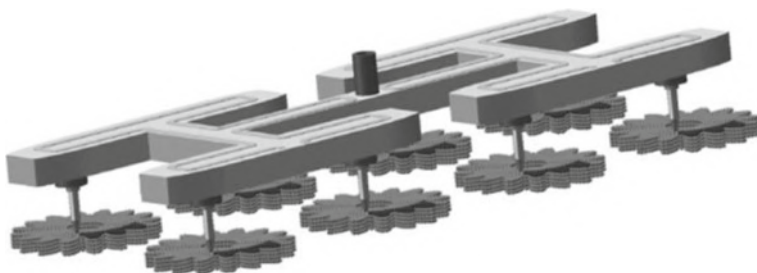
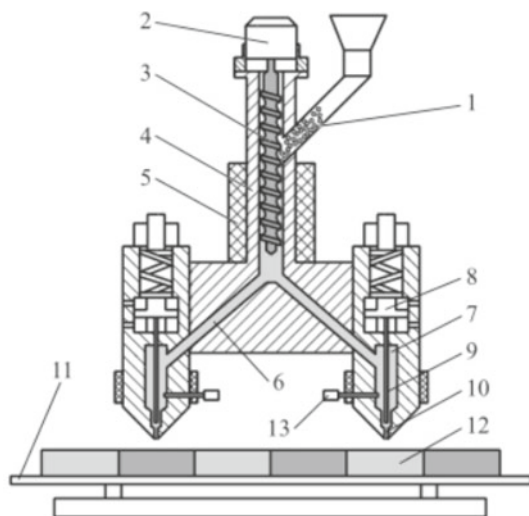


Fig. 3.9 The working principle of melt differential 3D printing



1-pellets; 2-drive motor; 3-screw; 4-barrel;
5-heating jacket; 6-hot runner; 7-valve cavity; 8-valve needle drive device;
9-valve needle; 10-nozzle; 11-substrate; 12-product; 13-pressure detection device

Fig. 3.10 Basic principles of melt differential 3D printing

According to the basic forming principle of melt differential 3D printing, the melt differential 3D printer was designed and manufactured (Fig. 3.11). According to the different driving methods, it can be divided into electromagnetic and pneumatic (Fig. 3.12). The melt differential 3D printing system includes two parts: a structural unit and a control unit. The structural unit includes a consumable plasticizing device, an on-demand extrusion device, and a stacking forming device. The control unit includes a motion control device, a temperature adjustment device, a consumable detection device, and a pressure feedback device.

The melt differential 3D printing molding method has the following characteristics.

- ① Adopt screw type feeding device. It can process thermoplastic pellets and powders. Avoid printing limitations of filamentary consumables. Extends the application range of fusion-stacked 3D printing.
- ② The needle valve structure is adopted as the melt extrusion control device. Avoid the shortcomings of open nozzles that are easy to drool. By controlling the opening and closing of the valve needle, the extrusion flow rate and extrusion time of the melt can be accurately controlled, and the accuracy of the melt “micro unit” can be improved.
- ③ Through the area division of the printing model, the 3D printing efficiency can be doubled by the method of multi-nozzle printing when preparing large-scale products.



Fig. 3.11 Different specifications of melt differential 3D printers

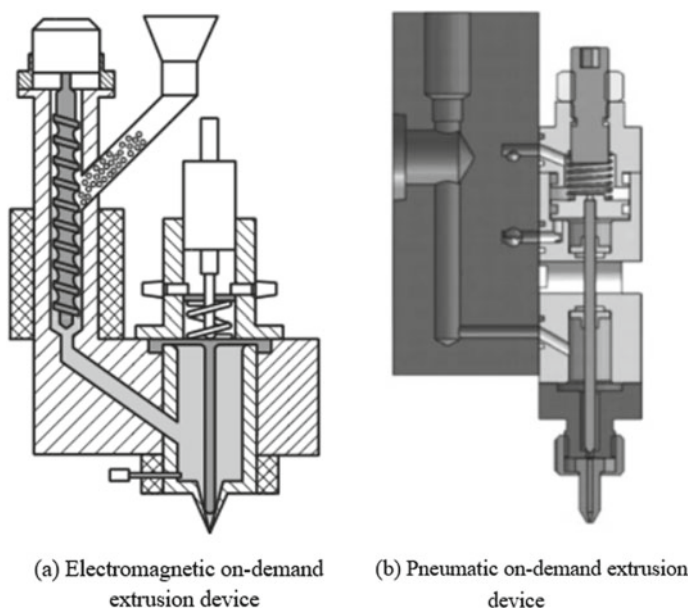


Fig. 3.12 Different driving methods

3.2.3 Theoretical Analysis of Melt Differential 3D Printing

In this section, we will study the theoretical model of the melt in sections according to the process sequence of the consumable melting section, the on-demand extrusion section, and the accumulation forming section.

(1) Research on precision transportation and pressure building model of melt

In order to realize the controllable extrusion of the melt, it is first necessary to ensure that the consumables are accurately conveyed in the consumables melting section and the pressure builds up stably at the entrance of the valve cavity. Therefore, the design parameters of the screw are very important for the stable operation of the entire system. Due to the limitation of the overall size of the 3D printer, the size of the melting and plasticizing section is much smaller than the design size of the ordinary extrusion device. Therefore, the calculation method of ordinary screw is not suitable for micro screw. This section draws on the related models of micro-extrusion rheological analysis [25] and screw-type melt extrusion rapid prototyping device [26, 27] to establish the relationship between screw size, speed, melt flow rate and die pressure. Lay a theoretical foundation for the design and manufacture of the melting and plasticizing section.

- ① *Screw type selection* In order to achieve uniform plasticization of thermoplastic consumables, and precise conveying and continuous pressure build-up during processing, a single screw with gradual groove depth can be selected. Groove-depth gradual change-type single screw generally includes a feeding section, a compression section and a metering section [28], as shown in Fig. 3.13. The feed section L_1 needs to ensure a stable supply of pellets and establish back pressure. For the screw, the groove depth H_1 of the feeding section is at least greater than the standard pellet diameter to ensure that the pellets in the hopper “feed” into the barrel. The compression section L_2 is used to compact the molten material and discharge air. The metering section L_3 ensures that the melt is squeezed into the valve cavity with a stable flow and pressure.

The size of the screw has an important influence on the plasticization and pressure building of consumables [29]. The relevant parameters are shown in Fig. 3.14.

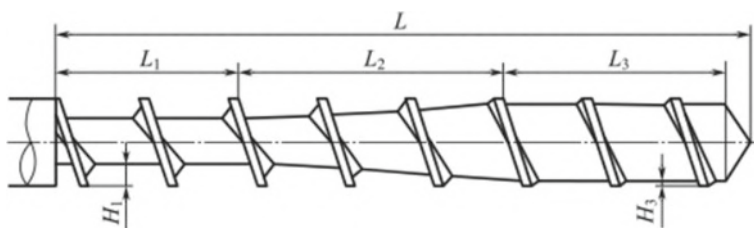
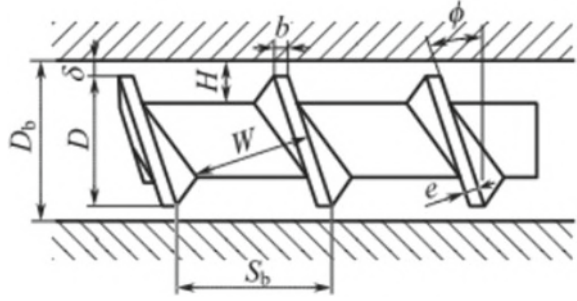


Fig. 3.13 Diagram of the distribution of each section of a single screw with gradual groove depth

Fig. 3.14 The geometrical parameters of the screw



- a. Constant screw length parameters: barrel inner diameter D_b , screw outer diameter D , screw pitch S_b .
 - b. Screw radial parameters: helix angle ϕ , the normal width of the groove W , the normal width of the screw edge e , the axial width of the screw edge b .
 - c. Screw axial parameters: feeding section screw groove depth H_1 , metering section screw groove depth H_3 .
- ② The relationship between screw speed and extrusion flow According to the structure and geometrical parameters of each section of the groove-depth-gradual single screw, the relationship between the screw speed and the extrusion flow rate is established. Due to the small diameter of the micro screw, the arc surface effect cannot be ignored. Therefore, the infinite plate theoretical formula often used to guide the design of extruders is difficult to apply [30].

Li et al. [31] analyzed the single-screw extrusion formula under actual boundary conditions, and performed analysis and calculation under isothermal and Newtonian fluid conditions. The expression of the relationship between the dimensionless melt flow rate and the geometric parameters of the screw, the speed and the viscosity of the consumables is proposed:

$$Q_z^* = F_d^* - F_p^* p_z \quad (3.1)$$

Among:

$$F_d^* = \frac{1 - H_3/R_b}{H_3/R_b} \left(2\pi \tan \phi - \frac{e}{R_b} \right) f_{Q1} + \frac{0.27 H_3/R_b \times (2 - H_3/R_b)}{\left(2\pi \tan \phi - \frac{e}{R_b} \right) \cos \phi} \quad (3.2)$$

$$F_p^* = \frac{1}{12} - \frac{0.05 H_3/R_b}{\left(2\pi \tan \phi - \frac{e}{R_b} \right) \cos \phi} \quad (3.3)$$

$$p_z = \frac{1}{\mu} \times \frac{\partial p}{\partial Z} \times \frac{H_3^2}{R_b \omega \cos \phi} \quad (3.4)$$

$$f_{Q1} = 0.5 \frac{H_3}{W} - 0.32 \left(\frac{H_3}{W} \right)^2 \quad (3.5)$$

In the formula, R_b is the screw outer diameter radius; p is the melt pressure; F_d^* is the drag flow influence parameter; F_p^* is the pressure flow influence parameter.

According to the theoretical model of Li, Wang [32] obtained the extrusion flow formula (3.6) of the micro screw after mathematical transformation:

$$Q_z = F_d^*(R_b \cos \phi W H_3) \omega - F_p^* \left(\frac{1}{\mu} \times \frac{P_1}{l_3} W \sin \phi H_3^2 \right) \quad (3.6)$$

Among them, the flow formula includes the drag flow Q_d caused by the rotation of the screw

$$Q_d = F_d^*(R_b \cos \phi W H_3) \omega \quad (3.7)$$

And the backflow caused by extrusion pressure during the flow process, referred to as pressure flow Q_p

$$Q_p = F_p^* \left(\frac{1}{\mu} \times \frac{P_1}{l_3} W \sin \phi H_3^2 \right) \quad (3.8)$$

In the process of melt conveying and pressure building, in order to establish a linear corresponding relationship between the extrusion flow rate and the screw speed, the influence of the reflux on the overall flow rate should be reduced. According to formula (3.8), the parameters that affect the pressure flow include melt viscosity, length of metering section, normal width of screw groove, helix angle and depth of screw groove, etc. According to the formula, the pressure flow is proportional to the third power of the groove depth, so although reducing the groove depth affects the drag flow, it will greatly reduce the pressure flow. In addition, the pressure flow is inversely proportional to the length of the metering section. Therefore, increasing the length of the metering section can also reduce the pressure flow. According to practical experience, reducing the gap δ between the barrel and the screw can also reduce the pressure flow.

Based on the above analysis, the linear relationship between extrusion flow rate and screw speed can be obtained, as shown in formula (3.9):

$$Q_z = 2\pi k F_d^*(R_b \cos \phi W H_3) n \quad (3.9)$$

Among them, $k = 1 - Q_p/Q_d$, $\omega = 2\pi n$, n is the screw speed. In order to reduce the influence of pressure flow on the linear relationship, the value of k should be greater than 0.95.

- ③ The relationship between screw speed and valve cavity back pressure From Fig. 3.10, it can be seen that the melt is plasticized and pressure-built in the

consumable melting section, and then transported to the valve cavity through the hot runner, and finally extruded through the nozzle. It can be determined that the melt flow rate Q_z delivered into the valve cavity is equal to the total flow rate Q_n extruded through each nozzle, that is:

$$Q_z = mQ_n \quad (3.10)$$

Among them, m is the number of printable nozzles.

Since the nozzle outlet diameter is generally less than 1 mm, it can be regarded as a micro hole. When the flow at the nozzle is assumed to be stable, incompressible, and laminar, refer to the Hagen–Poiseuille formula [33]:

$$Q_n = \frac{\pi D_n^4}{128 \mu L_n} \Delta p \quad (3.11)$$

In the formula, D_n is the nozzle diameter; L_n is the nozzle length; Δp is the valve cavity back pressure.

According to formula (3.9) ~ formula (3.11), we can get:

$$\Delta p = \frac{256 \mu L_n k F_d^* (R_b \cos \phi W H_3)}{m D_n^4} n \quad (3.12)$$

Through the above research, the linear relationship between the screw speed, the extrusion flow rate and the back pressure of the valve cavity in the micro-screw extrusion system is established. Therefore, the closed-loop feedback can be realized by detecting and controlling the back pressure of the valve cavity, and then the screw speed can be controlled to achieve the purpose of precise control of the melt extrusion flow.

(2) Analysis of melt on-demand extrusion process and melt dynamics

Through the theoretical analysis of the consumable melting section, the method of controlling the screw speed to accurately adjust the extrusion flow rate and the back pressure of the valve cavity is obtained. Under this premise, the flow process of the melt in the on-demand extrusion section is studied, and the influence of the movement of the valve needle on the melt flow is analyzed.

① Analysis of melt on-demand extrusion process The process of melt extrusion on demand is divided into the following 3 steps.

- a. When the needle valve is closed, the melt fills the entire valve cavity under the pressure of the melting section of the consumables and builds up the back pressure of the valve cavity. Because the nozzle is in a closed state, the melt cannot flow out of the nozzle, and the outside air cannot enter the valve cavity.
- b. When the valve needle moves upward under the action of external force, the inner mouth of the nozzle opens. Under the action of back pressure, the melt

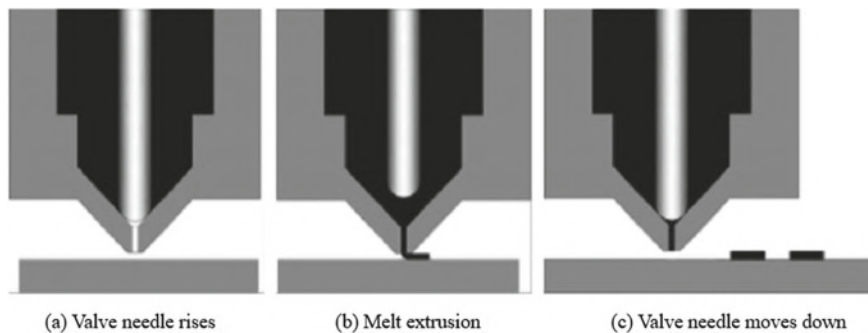


Fig. 3.15 Melt on-demand extrusion process

quickly fills up the holes and nozzles left by the rising of the valve needle, and flows out of the nozzles onto the substrate, resulting in a drag effect with the movement of the substrate. When the needle valve rises to the highest stage and remains stationary, the nozzle is in a normally open state. Under the state of constant back pressure, the extrusion flow rate of the melt is determined by the extrusion time.

- c. When the valve needle moves downward, the melt at the lower end of the valve needle accelerates and is extruded from the nozzle. When the valve needle contacts the upper edge of the nozzle, the inner mouth of the nozzle is closed and the extrusion stops. The extruded melt moves with the substrate to other positions, and a little melt remains in the nozzle.

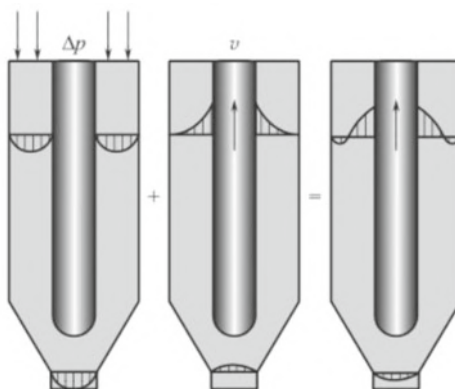
The on-demand extrusion process of the melt is shown in Fig. 3.15.

- ② Melt dynamics analysis According to Yue [34] on the fluid dynamics analysis of the spray dispensing process and Li [35] on the research of plastic droplet ejection technology, it can be known that when the valve needle moves, the melt in the valve cavity is subjected to back pressure to produce pressure flow. That is, the pressure difference flows. And the drag flow generated with the movement of the valve needle, that is, the shear flow. The upper end of the nozzle and the melt in the nozzle flow due to the superposition of the static pressure generated by the back pressure and the dynamic pressure generated by the movement of the valve needle.

When the valve needle moves upward, its melt flow rate distribution is shown in Fig. 3.16. The flow velocity distribution of the melt in the valve cavity is the difference between the downward pressure difference flow and the upward drag flow. The upper edge of the nozzle is the difference between the static pressure differential flow and the dynamic pressure differential flow. When the valve needle moves too fast and the back pressure is small, it will cause the air at the nozzle to back into the valve cavity.

When the valve needle moves downwards, the melt flow rate distribution is shown in Fig. 3.17. The flow velocity distribution of the melt in the valve cavity is the sum

Fig. 3.16 Melt flow rate distribution diagram when the valve needle rises (for a clear description, the nozzle diameter is enlarged)



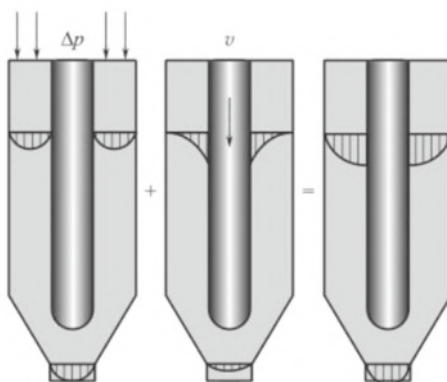
Δp -valve cavity back pressure; v -valve needle movement speed

of the downward pressure difference flow and the downward drag flow. The upper edge of the nozzle is the sum of the static pressure differential flow and the dynamic pressure differential flow. When the valve needle moves too fast, the melt jet will appear.

Through the above analysis, it is found that when the needle valve reciprocates, the pressure value of the upper edge of the nozzle is in an unstable state, which will have a greater impact on the extrusion flow and flow rate of the melt, which is not conducive to the precision control of the 3D printing process. Through the analysis, it can be known that the back pressure value, the movement speed of the valve needle, the movement distance, the ratio of the valve needle diameter to the valve cavity diameter, the nozzle diameter and other parameters will all affect the flow of the melt.

(3) Theoretical analysis of differential filling in melt zone

Fig. 3.17 Melt velocity distribution diagram when the valve needle moves down



Δp -valve cavity back pressure; v -valve needle movement speed

- ① Fused deposition molding bonding and deformation mechanism Based on the diffusion bonding mechanism [37], Jiang [36] proposed that the bonding state of fused deposition depends on the number of diffusion molecules that cross the stacking interface. The higher the bonding interface temperature, the longer the interface temperature is maintained, and the better the bonding performance. Adhesive performance can be expressed by interface temperature and molecular diffusion time, as shown in formula (3.13) and formula (3.14):

$$\Phi = \frac{1}{s} \int_0^{\infty} \int_0^s \xi(T) \cdot e^{-\frac{k}{T(x,y)}} dx dy dt \quad (3.13)$$

$$\xi(T) = \begin{cases} 1, & T \geq T_c \\ 0, & T < T_c \end{cases} \quad (3.14)$$

In the formula, s is the effective bonding area; t is the diffusion time; T is the interface temperature; T_c is the glass transition temperature.

In the actual printing process, both the melt temperature and the substrate temperature will affect the diffusion process. Therefore, an appropriate increase in the temperature of the two is conducive to enhancing the strength of the product [38]. For 3D printing of large products, as shown in Fig. 3.18, because the printing path is too long, when the nozzle moves to the point b adjacent to the fuse, the temperature at point a has been greatly reduced, which affects the bonding effect. Therefore, path planning should be used to shorten the printing time at adjacent locations to ensure that the temperature is maintained at a higher-level during fuse bonding. By means of regional differential filling, the printing area is evenly divided into multiple cells, which can reduce the phenomenon that the path is too long and affect the bonding effect, and improve the overall product strength.

In addition, due to the phase change of the fuse during the cooling process, the phenomenon of cooling shrinkage occurs, resulting in internal stress and warping deformation in the product, which seriously affects the accuracy of the product [39]. The main factors that affect the warpage are the cooling shrinkage rate of consumables, the number of stacked layers, the stacking path, and the temperature of the substrate and the fuse [40].

Aiming at the problem of product warpage deformation, Wang [41] studied the mathematical model of warpage deformation of fused deposition molding. The

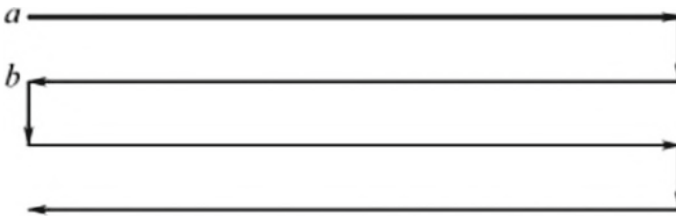


Fig. 3.18 Schematic diagram of long-path printing of large products

strategy of sub-area scanning is proposed, which can effectively reduce the warpage deformation rate of the product. For long products, the vertical printing effect is better than horizontal printing. Huang [42] proposed a parallel raster scan path. This path can optimize the temperature field and reduce the deformation rate of the product. Relevant studies have proved that when the consumables, models and forming conditions are determined, the temperature field can be uniformed by changing the scanning path, reducing the internal stress of the product, and meeting the requirements of reducing warpage deformation.

According to the principle of melt calculus, the author adopts multi-nozzle to print by cell filling method, which can not only improve the efficiency of 3D printing, but also optimize the temperature field and reduce the warpage and deformation of the product through the method of regional differential filling and accumulation.

- ② Cell differential multi-area filling method When printing three-dimensional products using the fusion accumulation method, files in the triangle grid (STL) format need to be layered, and at each layer, the nozzles fill in along a set path [43], as shown in Fig. 3.19.

However, when using the fusion accumulation method to prepare large-size products, there is a problem that the printing time is too long. In order to increase the processing efficiency of the product and improve the temperature field, the melt differential 3D printing has multiple nozzles uniformly arranged on the same runner plate. In order to support multi-nozzle printing, first divide the printing area evenly into multiple cells, as shown in Fig. 3.20.

Take the dual nozzle device shown in Fig. 3.10 as an example, assuming that the center distance between the dual nozzles is ΔL . According to Fig. 3.20, the dual-nozzle printer can fill two cells at the same time. According to the different shape of the model, the filling method can be divided into 2 types:

- a. When the filled cell is completely located in the printing area of the model, as shown in Fig. 20a, the two nozzles can fill the cell according to the same printing path.

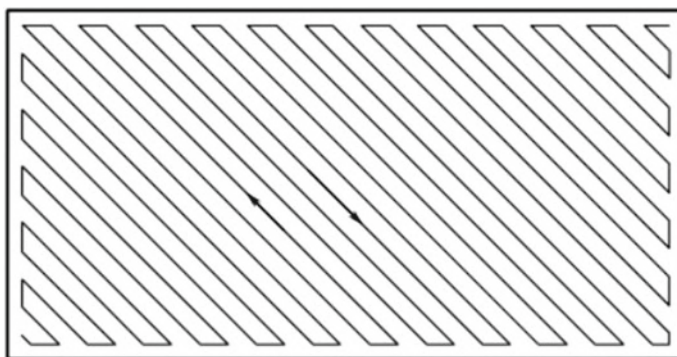


Fig. 3.19 Common filling path of fusion accumulation forming

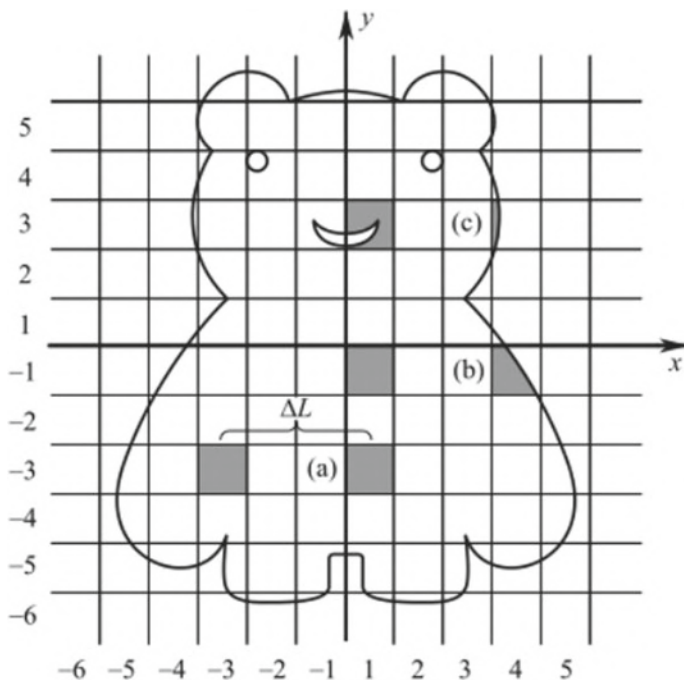


Fig. 3.20 The working principle of differential filling in the melt area

- b. When the filled cell part is located in the printing area of the model, see the positions (b) and (c) in Fig. 3.20. At this time, the actual filling area of the dual nozzles is different. According to the actual filling area, the melt "micro unit" can be extruded by opening and closing the needle valve to ensure accurate filling.

The cell size setting should be based on the nozzle center spacing and the actual size of the product. Generally, it should be ensured that the distance between the nozzle centers is an integer multiple of the cell size. And most of the model printing area is filled according to method (a) to reduce the flow fluctuation caused by opening and closing the needle valve.

When the cell size is extremely small, the printing area becomes discretized. At this time, melt droplets are generated by high-frequency opening and closing of the needle valve. Each droplet corresponds to a cell to be filled. Through melt droplet stacking 3D printing method, the high precision of product printing is realized.

(4) Feasibility analysis of melt micro-droplet jetting

In summary, cell filling by melt droplets is beneficial to the improvement of product printing accuracy. This section analyzes the feasibility of melt micro-droplet jetting and lays the foundation for melt droplet stacking 3D printing.

- ① Introduction to micro-droplet jetting technology Inkjet printers were the first equipment to apply micro-droplet jetting technology. At present, the micro-droplet jetting has been applied in the field of 3D printing, such as the 3D printing equipment of Stratasys in the United States. According to the method of micro-droplet jetting, micro-droplet jetting can be divided into two types: continuous ink-jetting (CIJ) and drop-on-demand (DOD). The jetting process mainly includes valve control type, electrostatic type, thermal bubble type, piezoelectric type, electric field deflection type and micro syringe type [44].

The micro-droplet jetting technology for high-viscosity liquids mainly adopts valve-controlled and piezoelectric on-demand jetting processes. For example, the mechanical jet dispensing technology [45] and the pneumatic diaphragm droplet jet technology [46] researched by Huazhong University of Science and Technology. The piezoelectric micro-droplet distribution technology based on displacement amplification mechanism [47] and the micro-distribution technology of high-viscosity liquid with piezoelectric ceramic drive striker [48] are researched by Harbin Institute of Technology. The piezoelectric-gas hybrid driven jet dispensing technology [49] and the piezoelectric-hydraulic amplified jet dispensing technology [50] researched by Jilin University. The above technologies mainly use small molecular weight resin-based colloids as consumables for electronic packaging, microfluid distribution, and micro-optical device preparation.

Polymer melt is a typical non-Newtonian fluid, and its viscosity is affected by temperature and shear. Compared with the consumables commonly used for micro-droplet jetting, it has the characteristics of high viscosity and high temperature heating. At present, there are few related researches on polymer melt micro-droplet jetting. Therefore, this paper analyzes the feasibility of polymer melt micro-droplet jetting by studying the mechanism of micro-droplet jetting.

- ② Research on micro-droplet jetting mechanism The ideal micro-droplet jetting process is shown in Fig. 3.21. The forming process mainly includes 4 stages: liquid column extrusion and elongation, liquid column necking, liquid column shearing, micro-droplet falling [51]. However, in the actual micro-droplet forming process, the liquid column is difficult to break or break into multiple irregular micro-droplets [52]. Therefore, it is necessary to conduct a theoretical analysis of the micro-droplet jetting process to determine the influence of the forming parameters.

Kang [53] believed that the jetting process satisfies the Navier–Stokes equation, and proposed the fluid motion equation under the action of gravity and surface tension. The formula is as follows:

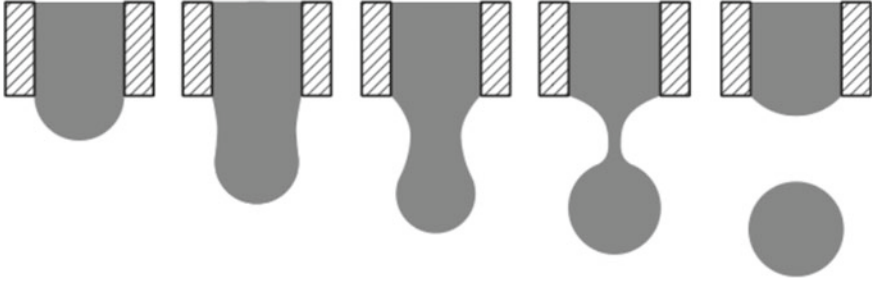


Fig. 3.21 Schematic diagram of free micro-droplet forming process

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial z} = 0 \quad (3.15)$$

$$\begin{aligned} \frac{\partial}{\partial t}(\rho u) + \nabla \cdot \rho V u = & -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left(2\mu \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial v}{\partial x} + \mu \frac{\partial u}{\partial y} \right) \\ & + \frac{\partial}{\partial z} \left(\mu \frac{\partial u}{\partial z} + \mu \frac{\partial \omega}{\partial x} \right) + F_x^\sigma + \rho g_x \end{aligned} \quad (3.16)$$

$$\begin{aligned} \frac{\partial}{\partial t}(\rho v) + \nabla \cdot \rho V v = & -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left(\mu \frac{\partial v}{\partial x} + \mu \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial y} \left(2\mu \frac{\partial v}{\partial y} \right) \\ & + \frac{\partial}{\partial z} \left(\mu \frac{\partial v}{\partial z} + \mu \frac{\partial \omega}{\partial y} \right) + F_y^\sigma + \rho g_y \end{aligned} \quad (3.17)$$

$$\begin{aligned} \frac{\partial}{\partial t}(\rho \omega) + \nabla \cdot \rho V \omega = & -\frac{\partial p}{\partial z} + \frac{\partial}{\partial x} \left(\mu \frac{\partial \omega}{\partial z} + \mu \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left(\mu \frac{\partial \omega}{\partial z} + \mu \frac{\partial v}{\partial y} \right) \\ & + \frac{\partial}{\partial z} \left(2\mu \frac{\partial \omega}{\partial z} \right) + F_z^\sigma + \rho g_z \end{aligned} \quad (3.18)$$

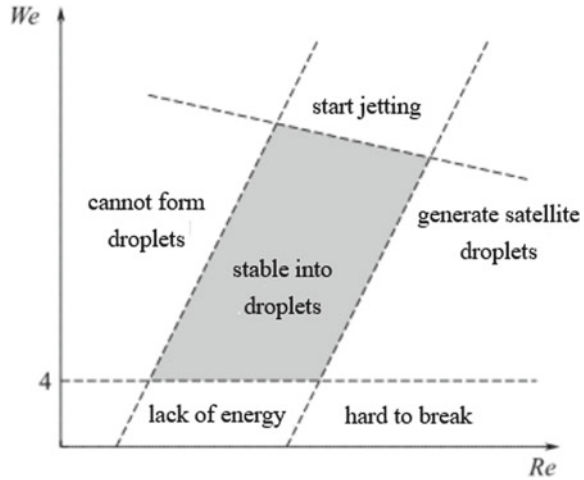
Among them, u , v , ω represent the velocity component value in the corresponding direction; ρ , p , μ represent density, pressure and viscosity; F^σ represents the surface tension between fluid and air; ρg represents gravity.

According to the formula, the micro-droplet jetting process is affected by gravity, inertial force, surface tension and viscous force. Therefore, the density, jet speed, surface tension coefficient and viscosity of the consumables determine the effect of micro-droplet forming. Derby [54] uses Reynolds number (Re), Weber number (We) and Orezog number (Oh) to characterize injection characteristics:

$$Re = \frac{v \rho d}{\mu} \quad (3.19)$$

$$We = \frac{v^2 \rho d}{\gamma} \quad (3.20)$$

Fig. 3.22 Restrictions on free droplets forming



$$Oh = \frac{\sqrt{We}}{Re} = \frac{\mu}{(\gamma \rho d)^2} \quad (3.21)$$

Among them, d refers to the nozzle diameter.

Reis [55] proved through experiments that the conditions for stable ejection of droplets are: $1 < Z < 10$; $Z = 1/Oh$. Duineveld [56] proved through experiments that when the We number is less than 4, the droplet lacks enough energy to break through the constraint of surface tension, and the liquid column is difficult to break. Stow [57] proved through experiments that when $We^{1/2}Re^{1/4} > 50$, the jet phenomenon occurs due to the excessive kinetic energy of the liquid, and the droplet cannot be formed. Figure 3.22 lists the restriction conditions for droplet formation [58].

- ③ Realization of polymer melt micro-droplet jetting Based on the limitations of liquid droplet ejection summarized by the predecessors, the requirements of polymer melt droplet ejection on the forming process and the characteristics of consumables are studied.

Poly(lactic acid) (PLA) consumables commonly used in melt accumulation forming are the research objects [59].

Trademark: PLA6252D, American Nature Works company;

Density ρ : 1.08 g/cm³ (210 °C melt);

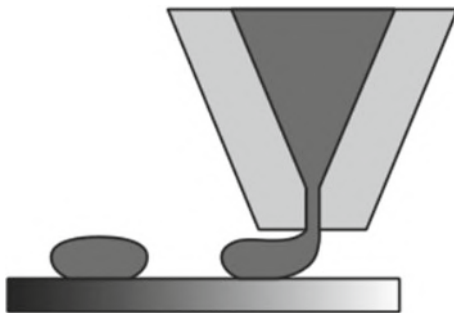
Viscosity μ : about 15 Pa·s;

Surface tension γ : about 24 mN/m;

Nozzle diameter is set to 0.4 mm.

Substituting the above values into formula (3.21), we get: $Oh = 1395.4$, $Z = 0.00072$. According to the realization conditions of stable droplet ejection, PLA belongs to the category of difficult droplets. The related parameters of other polymer

Fig. 3.23 Schematic diagram of passive micro-droplet forming process



materials are similar to those of polylactic acid consumables. The above analysis proves that due to the high viscosity of polymer melt, droplet formation cannot be achieved by droplet ejection. The viscosity of consumables can be reduced by material modification to achieve spray forming, or by increasing the nozzle diameter. But taking the droplet forming of PLA consumables as an example, to achieve free droplet ejection, the nozzle diameter should be greater than 150 μm , which does not meet the actual processing conditions.

It is difficult for polymer melts to achieve droplet formation in a free-dropping manner. But it can be processed by passive droplet forming, as shown in Fig. 3.23. The valve needle opens and closes at high frequency to discretize the melt extrusion process. At the same time, the distance between the substrate and the nozzle is shortened, and the viscous force between the melt at the nozzle is offset by the viscous force between the substrate and the melt, and the passive droplet formation of the melt is realized.

(5) The influence of valve control system parameters on melt extrusion

Through the above analysis of melt on-demand extrusion process and melt dynamics, the process of melt extrusion in the valve cavity is a combined process of pressure differential flow driven by back pressure and shear flow generated by valve needle movement. Parameters such as valve cavity back pressure value (p), valve needle movement speed (v), the ratio of the valve needle diameter (ϕ_v) to the valve cavity diameter (ϕ_c), the maximum movement distance of the valve needle (L_v), the nozzle diameter (ϕ_n), nozzle length (L_n) will affect the flow of melt. Therefore, this section will use the method of numerical simulation to analyze the influence of relevant parameters on the melt extrusion flow by using the Fluent simulation software, and provide theoretical guidance for melt on-demand extrusion control.

The influence of nozzle diameter (ϕ_n) and nozzle length (L_n) on the melt flow rate can be determined by the Hagen-Poiseuille formula. Therefore, in terms of geometric parameters, this section mainly analyzes the influence of the valve needle diameter (ϕ_v), the valve cavity diameter (ϕ_c), and the maximum movement distance of the valve needle (L_v) on the melt flow. The relevant geometric model is shown in Fig. 3.24.

Fig. 3.24 Physical model and parameter variables

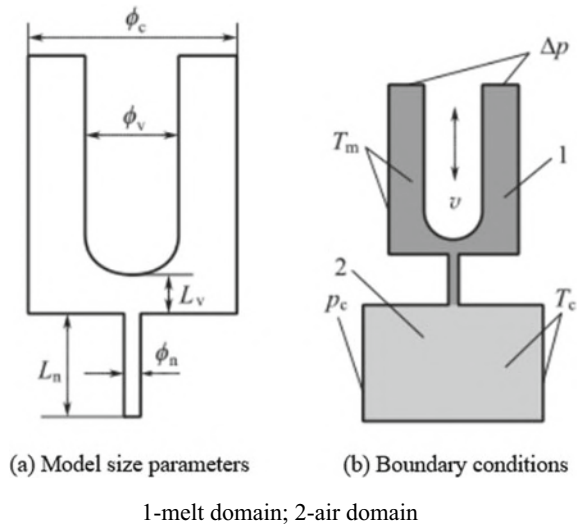


Figure 3.25 shows the effect of different valve needle movement speeds on melt extrusion flow. With the increase of the valve needle movement speed, the melt extrusion flow rate increases. When the moving speed is 0 m/s, except for the small fluctuations in the initial flow, the steady flow state is maintained. When the valve needle is far from the nozzle, the flow rate at the nozzle increases slowly, and the flow rate fluctuates smoothly. When the valve needle moves closer to the nozzle, the flow rate at the nozzle increases rapidly until the valve needle closes the nozzle and the flow rate drops to zero. When the valve needle is close to the nozzle, the higher the valve needle movement speed, the greater the disturbance to the melt extrusion flow.

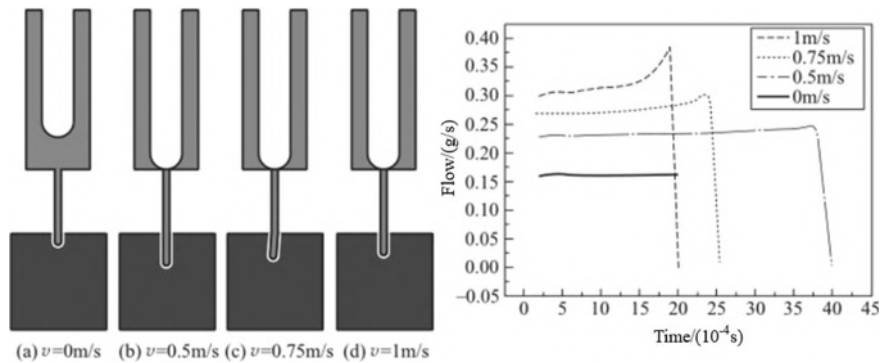
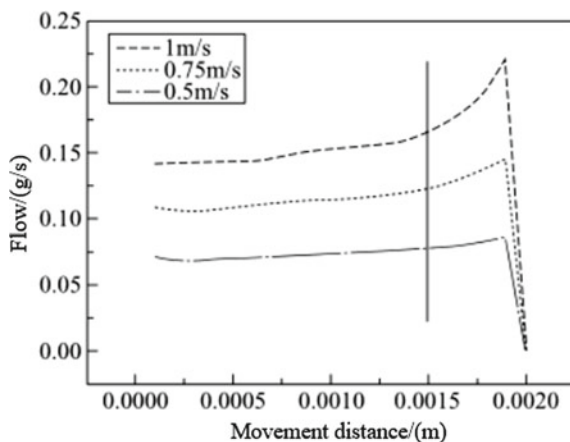


Fig. 3.25 The influence of different valve needle movement speed on the melt extrusion flow and the flow fluctuation curve at the nozzle

Fig. 3.26 The flow fluctuation curve at the nozzle (when the valve cavity back pressure is not considered)



After removing the influence value of the valve cavity back pressure on the melt flow, analyze the fluctuation of the melt flow at different positions of the valve needle, as shown in Fig. 3.26. About the first 3/4 part of the valve needle moving towards the nozzle, there is no large fluctuation in the flow, and the flow has a linear relationship with the movement speed of the valve needle. When the distance from the nozzle is about 0.5 mm, the flow rate increases greatly. But when the valve needle movement speed is low, the fluctuation is slower. Therefore, it can be considered that when the valve needle moves to a position closer to the nozzle, reducing the valve needle movement speed to reduce flow fluctuations and enhance the ability to control the extrusion flow.

Figure 3.27 shows the effect of the maximum displacement of the valve needle on the melt extrusion flow. When the valve needle remains stationary at the maximum position, the melt is steadily extruded under the action of the back pressure of the valve cavity. By analyzing the influence of the valve needle position on the melt flow, the valve needle position that has the least influence on the stable flow is found. When the pinhole distance is less than 0.5 mm, as the distance decreases, the melt flow rate decreases. When the pinhole distance is greater than 0.5 mm, the melt flow rate does not change significantly. It proves that the valve needle is too close to the nozzle, which will have a “blocking” effect on the melt flow and affect the efficiency of 3D printing. Therefore, under the size of this section, the pinhole distance should be greater than 0.5 mm. However, if the pinhole distance is too large, it will prolong the closing and opening and closing time, so it is best to set the pinhole distance to 0.5 ~ 1 mm.

Figure 3.28 shows the influence of the valve needle/valve cavity diameter ratio on the melt extrusion flow and the flow fluctuation curve at the nozzle. The valve needle/valve cavity diameter ratio affects the drag flow of the melt in the valve cavity. With the increase of the valve needle valve cavity diameter ratio, the melt flow rate increases under the same movement speed, and it does not conform to the linear growth law. When the movement speed is low and the valve needle valve cavity

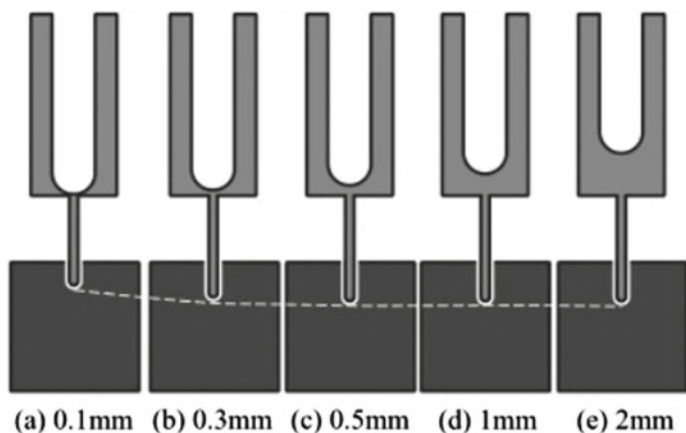


Fig. 3.27 The influence of the maximum displacement of the valve needle on the melt extrusion flow

diameter ratio is 0.25, the flow fluctuation is small. When the valve needle valve cavity diameter ratio is 0.75, the valve needle is closer to the nozzle, and the flow has a downward trend. It shows that when the valve needle diameter is large, it has a blocking effect on the pressure difference flow. When the valve needle diameter is small, the effect on the melt flow rate is small, and the 3D printing accuracy can be improved.

Figure 3.29 shows the effect of the valve needle movement speed/back pressure ratio on the melt extrusion flow and the flow fluctuation curve at the nozzle. When the valve needle is opened, the direction of shear flow and pressure difference flow are opposite. When $v/\Delta p$ is large, the melt may flow back and air enters the valve cavity. The melt flow rate decreases with the increase of $v/\Delta p$. When $v/\Delta p$ is greater

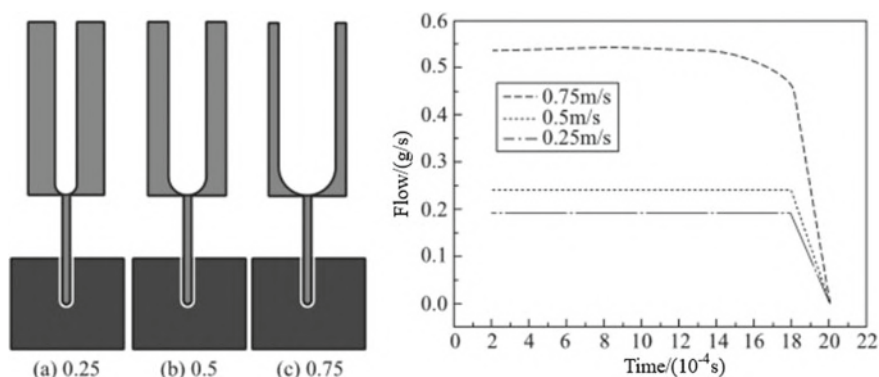


Fig. 3.28 The influence of the valve needle/valve cavity diameter ratio on the melt extrusion flow and the curve of the flow fluctuation at the nozzle

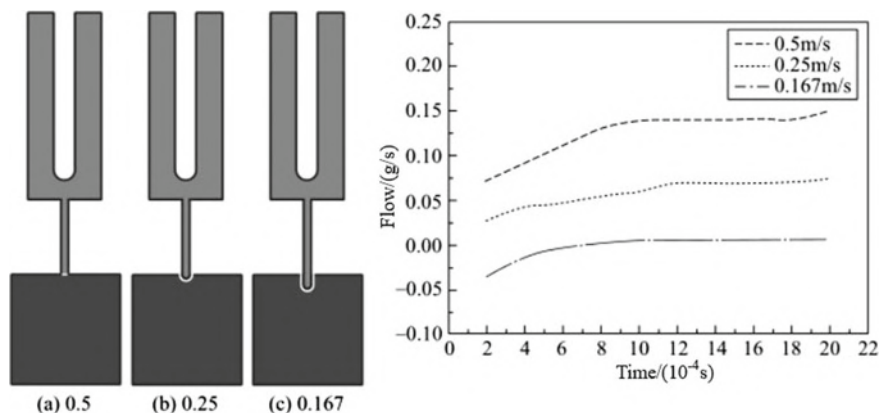


Fig. 3.29 The effect of the valve needle movement speed/back pressure ratio on the melt extrusion flow rate and the flow fluctuation curve at the nozzle

than 0.5, the melt will flow backwards. Therefore, in order to avoid the phenomenon of reverse flow, the back pressure of the valve cavity should be increased or the movement speed of the valve needle should be reduced. As the valve needle rises, the flow rate gradually increases. When it rises to about 0.5 mm, the flow rate remains stable, which is consistent with the previous analysis.

In summary, the following conclusions can be drawn:

- ① The reciprocating speed of the valve needle affects the extrusion flow rate by influencing the drag flow of the melt. When the valve needle moves down, the faster the movement speed, the greater the extrusion flow. And when the valve needle is closer to the nozzle, the disturbance to the extrusion flow is greater. Therefore, when approaching the nozzle position, stable extrusion can be achieved by reducing the speed, and the printing accuracy can be improved.
- ② When the movement distance is less than 0.5 mm, it will block the melt extrusion, reduce the flow rate, and affect the printing efficiency. When the movement distance is too long, the opening and closing time will be extended. Therefore, it is best to set the pinhole distance to 0.5 ~ 1 mm.
- ③ The valve needle valve cavity diameter ratio affects the drag flow of the melt in the valve cavity. As the diameter ratio increases, the extrusion flow rate increases. And the larger the diameter ratio, the larger the flow fluctuation. Therefore, a valve needle with a smaller diameter should be selected.
- ④ When the valve needle moves up, the direction of the shear flow and the pressure difference flow are opposite. When the valve needle movement speed/back pressure ratio is greater than 0.5, the melt will flow backwards. Therefore, in order to avoid the phenomenon of reverse flow, the back pressure of the valve

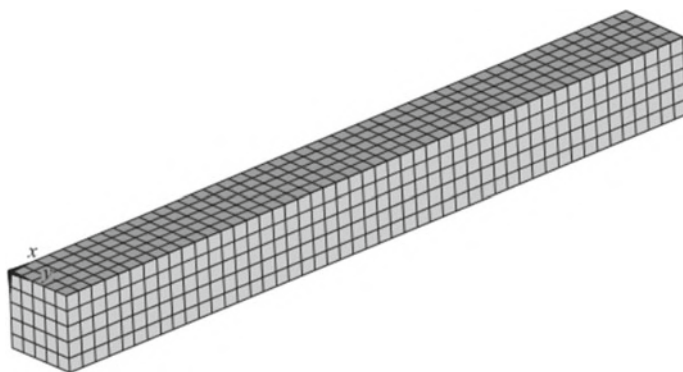


Fig. 3.30 Cuboid model and meshing

cavity should be increased or the movement speed of the valve needle should be reduced.

(6) The effect of differential filling in melt area on product accuracy

Through the aforementioned analysis of the differential filling theory of the melt area, the method of dividing cells and multi-nozzle printing for large products can greatly improve the efficiency of 3D printing, and improve the temperature field and bonding performance. In this section, the “life and death element method” is used for numerical simulation in view of the current situation that large-size fused deposition modeling products are prone to warping deformation. The rectangular parallelepiped with obvious change in aspect ratio is selected as the research object (see Fig. 3.30). The influence of the area differential cell size on the temperature field and stress field in the printing process is studied. The feasibility of reducing the warpage deformation by means of differential filling of the area is analyzed. Lay a theoretical foundation for improving the reduction of thermal stress and warpage during the processing of large products.

Because in the process of fusion and accumulation, the consumables undergo from solid state heating and melting to cooling and solidification, and are affected by the printing path and its own performance, the heat transfer and deformation mechanisms are very complicated. Therefore, in order to simplify the calculation, the following assumptions are made:

- a. Assuming that the melt extrusion temperature is the same, set it to 180 °C. The ambient temperature is set to 30 °C. Heat conduction and convection heat exchange between the melt and the air and the cooled part;
- b. Assuming that when the consumable is cooled from the melt to a solid, all the latent heat is released uniformly;
- c. It is assumed that the density of the consumables remains unchanged under different phases and different temperature states.

- ① **Single nozzle multi-cell printing method** According to the aforementioned differential filling theory of melt area, the printing area is evenly divided into multiple cells. First, a single nozzle is used for printing, and the influence of area division on temperature field and stress field is analyzed.

According to Fig. 3.31, the printing path is divided into 4 types. Figure 3.31a is the method without cell division, and the printing path is from point a to point b. Figure 3.31b ~ d are evenly divided into 2, 4, and 8 cells respectively. The example shown in the figure prints 5 layers, the second layer moves up one layer at point b, and then moves along the track from point b to point a, and then proceeds in sequence until the printing is completed.

Figure 3.32 shows the temperature field distribution of different division methods at the end of printing. It can be seen from Fig. 3.32a that in the direction of the short side of the same layer, the temperature of one side is higher than the other side. With the refinement of the cell division, the temperature distribution gradually becomes uniform, and there is only a higher temperature near the printing point.

The starting point a is selected as the research object, and the temperature change of a point with the printing time is studied. As can be seen in Fig. 3.33, different paths have a certain impact on the temperature change at point a, which is specifically reflected in:

- a. As the cells become thinner, the long-side printing path shortens. Therefore, when printing from point a to returning to point a, the time is shortened exponentially,

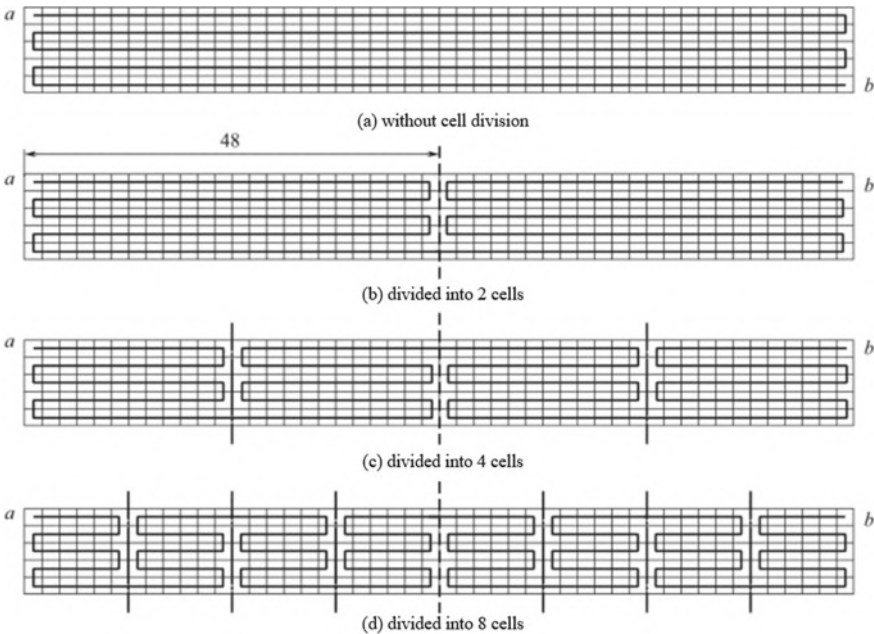


Fig. 3.31 Schematic diagram of the printing path of different cell division methods

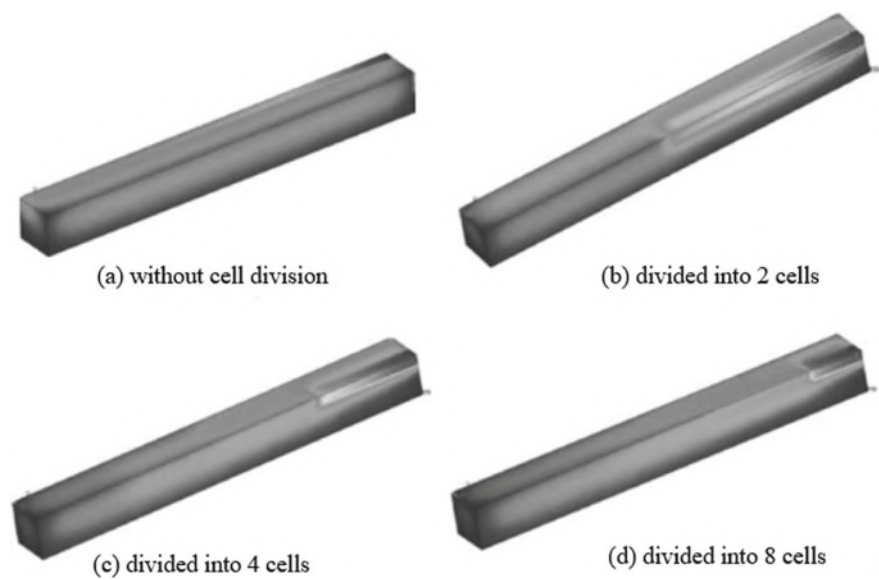


Fig. 3.32 Temperature field distribution of different division methods at the end of printing

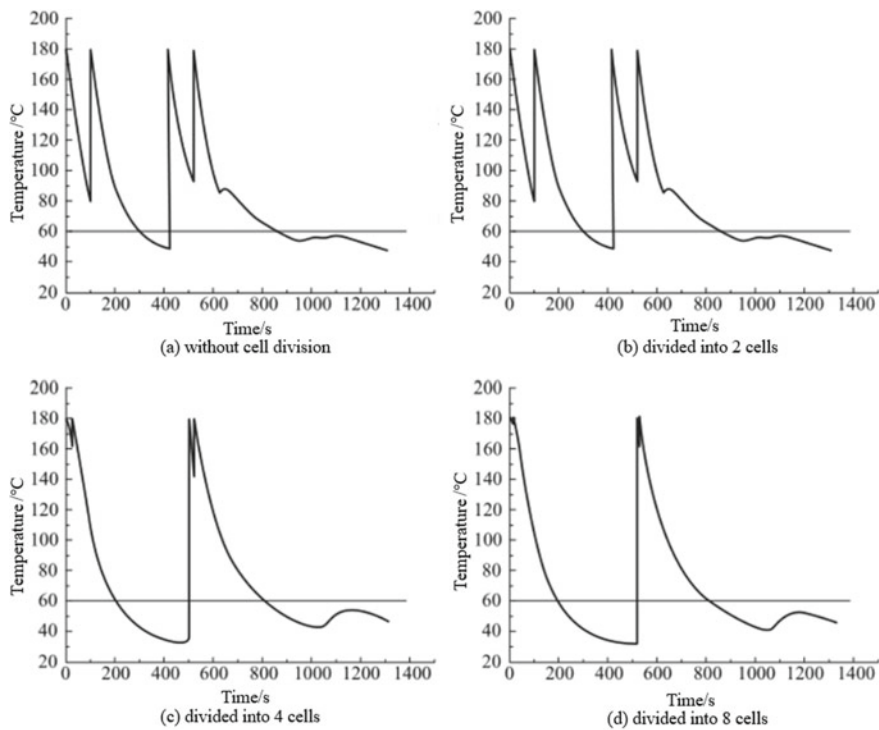


Fig. 3.33 Temperature distribution of point a in different division methods

- and the temperature drop is lower, which is conducive to the bonding between the fuses and improves the tensile strength between the paths. As shown in Fig. 3.33a, when returning to point again, the temperature has dropped to 78 °C. According to the theory of fused deposition bonding, the higher the maintaining temperature of the bonding interface, the better the bonding effect.
- As the floor height increases, the temperature at point a shows three large fluctuations in accordance with the path planning. They are the starting state, the movement to the end of the second layer, and the movement to the beginning of the fourth layer. The highest point is the starting temperature 180 °C, but the lowest point temperature is gradually decreasing.
 - Due to the different paths, the temperature change trend at point a is different. If the glass transition temperature of PLA material is set to 60 °C, the overall temperature of the method without cell division is higher than that of other division methods. The higher the degree of crystallinity, the greater the cooling shrinkage rate, which is prone to warpage.

Figure 3.34 shows the stress change diagram of different division methods after 1200 s printing. After hiding the constrained layer, it can be seen that the change of stress is basically consistent with the change of temperature field. The maximum stress is generated at the end of printing due to rapid cooling. And at the corners of the bottom layer, due to the long cooling time and faster heat dissipation, warping is easy to occur.

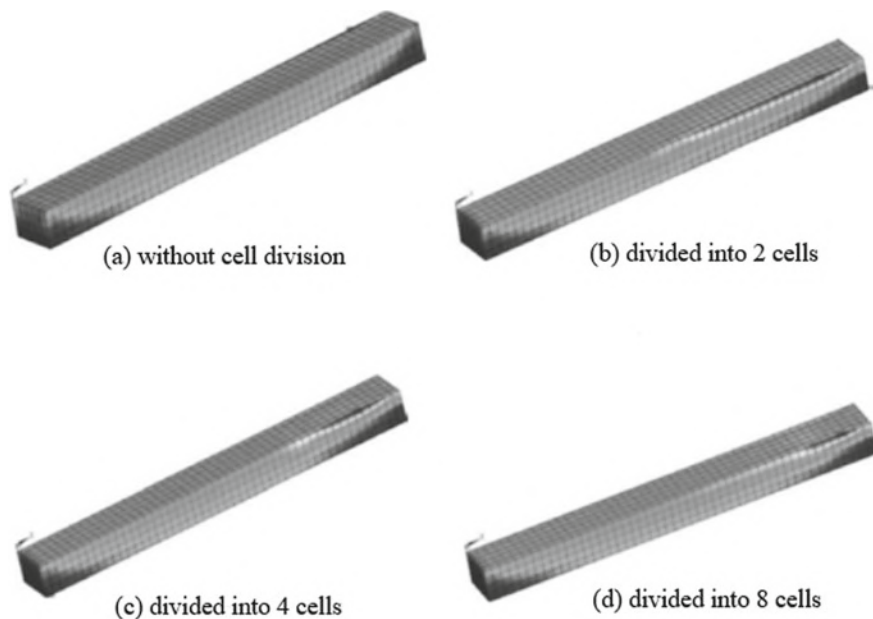


Fig. 3.34 Stress field distribution of different division methods

Fig. 3.35 Equivalent stress value under different division methods

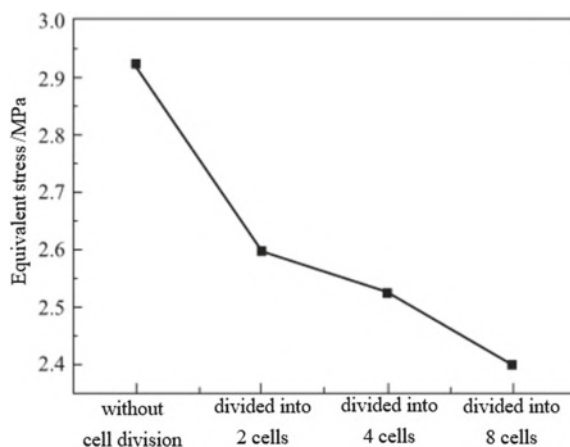


Figure 3.35 shows the equivalent stress values under different division methods. It can be seen that with the refinement of the cells, the equivalent stress gradually decreases to reduce the strain and reduce the possibility of warpage.

- ② Double print head multi-cell printing method According to Fig. 3.36, the printing path is divided into three types. Figure 3.36a shows the way of dividing the cell into two divisions. The printing path is from point a to point b, and point c to point d. Figure 3.36b and c are equally divided into four cells and eight cells, respectively. The printing path is also from point a to point b, and point c to point d. The example shown in the figure prints 5 layers, the second layer moves up one layer at point b, and then moves along the track from point b to point a, and then proceeds in sequence until the printing is completed.

Figure 3.37 shows the temperature field distribution during dual-nozzle printing. It can be clearly seen that there are two heating points in the case of dual-nozzle printing. The printing time is shortened, and the cooling time is short so that the temperature remains high.

The starting point a is selected as the research object, and the influence of single nozzle and double nozzle on the cooling effect is analyzed. As shown in Fig. 3.38, the specific performance is:

- In the initial result, the printing path is the same, so the temperature changes are the same.
- The path is shortened due to dual-nozzle printing, and the temperature at point a remains above the glass transition temperature at the end of printing.

Figure 3.39 shows the stress changes of dual-nozzle printing in different division modes after 600 s printing. After hiding the constrained layer, it can be seen that the change of stress is basically consistent with the change of temperature field. The stress concentration and warpage displacement are basically the same as that of single nozzle printing, but there are two maximum stress points in the first layer.

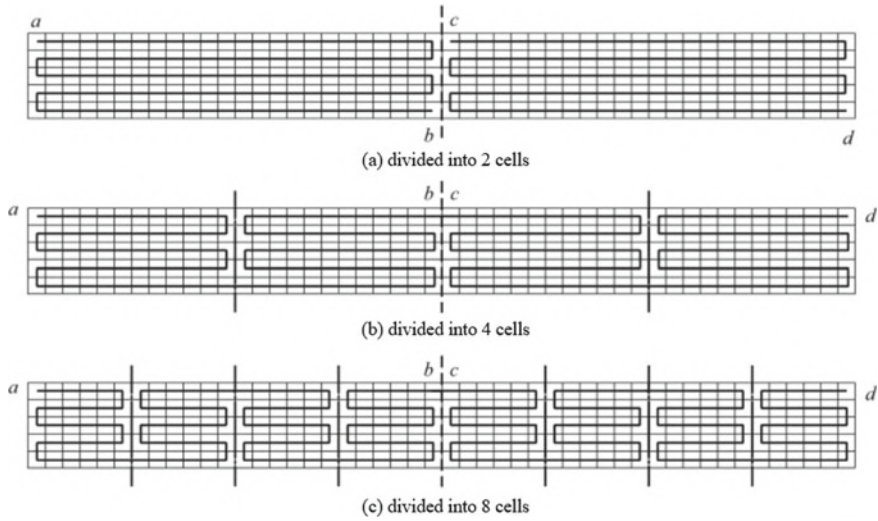


Fig. 3.36 Top view of different cell division methods in dual nozzles

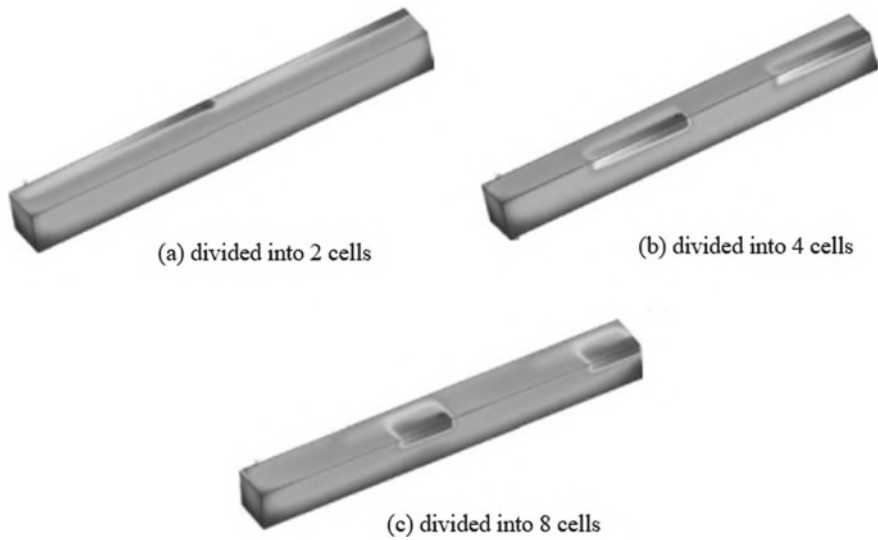


Fig. 3.37 Temperature field distribution of different division methods at the end of dual-nozzle printing

Figure 3.40 shows the equivalent stress values under different division methods under dual-nozzle printing, which shows a gradual decrease trend consistent with single-nozzle printing. But the overall value is greater than that of single-jet printing products. The reason is that it takes 600 s to complete the printing under dual-nozzle

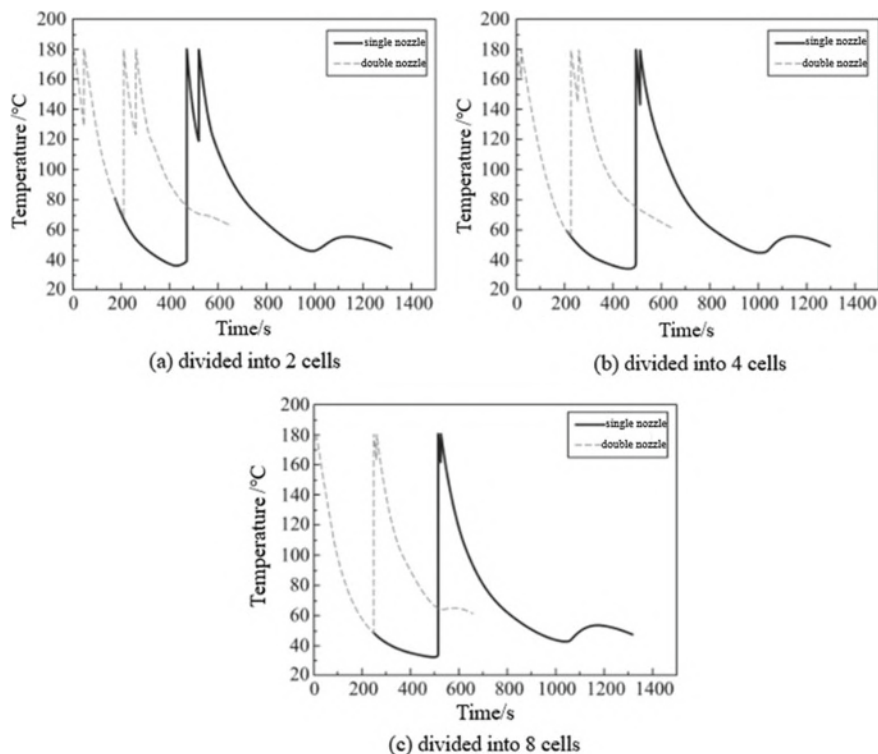


Fig. 3.38 Comparison of temperature field between single nozzle and multi-nozzle printing under different division methods

printing. The product has not been completely cooled, and thermal shrinkage has not occurred sufficiently, so the stress value is too large.

In this section, the “life and death element method” is used for numerical simulation based on the area differential filling method. The influence of the cell scale of regional differential filling on the temperature field and stress field of printed products is studied, and the following conclusions are drawn:

- As the cell size shrinks, the temperature field can be optimized during the deposition process. After printing, the equivalent stress of the product due to cooling shrinkage is reduced, which reduces the incidence of warpage.
- Multi-nozzle printing has shorter forming time than single-nozzle printing, and the temperature field in the deposition process is more uniform.

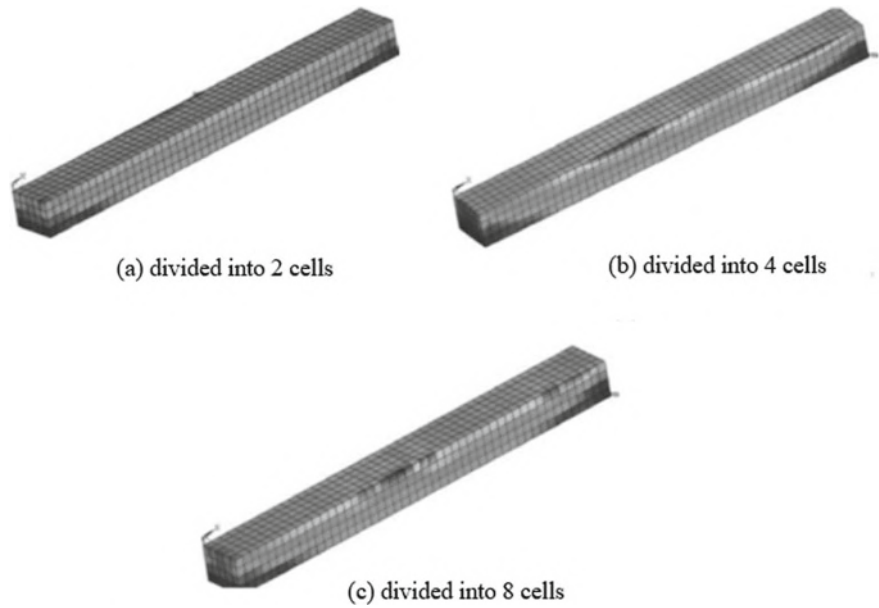
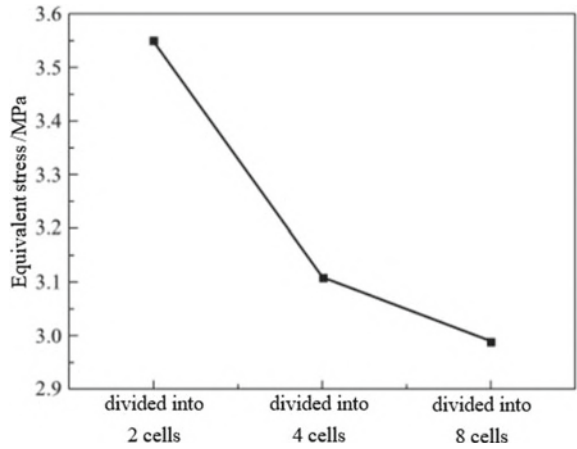


Fig. 3.39 The stress field distribution of dual-nozzle printing under different division methods

Fig. 3.40 Equivalent stress value under different division methods under dual-nozzle printing



3.2.4 Design of the Melt Differential 3D Printing Device

The melt differential 3D printing system includes two parts: a structural unit and a control unit. The structural unit includes a consumable plasticizing device, an on-demand extrusion device, and a stacking forming device. The control unit includes

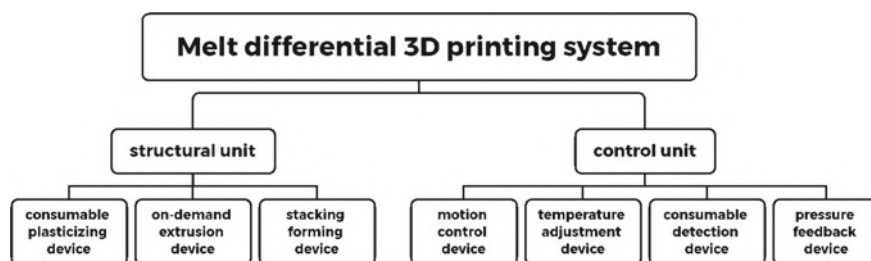


Fig. 3.41 Basic composition of melt differential 3D printing system

a motion control device, a temperature adjustment device, a consumable detection device, and a pressure feedback device. Its basic structure is shown in Fig. 3.41.

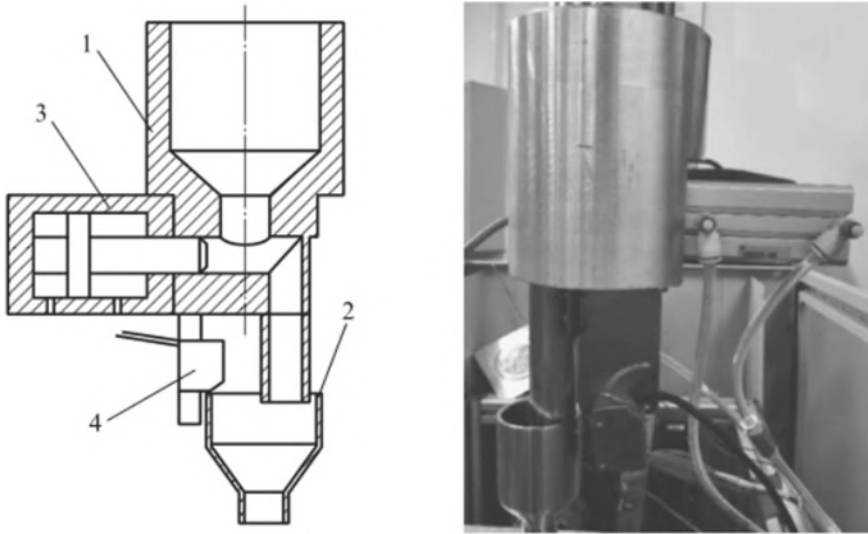
(1) Design of consumable plasticizing device

- ① *Design of automatic feeding device* Due to the small size of the barrel of the micro-screw extruder, the heat in the melting section and the metering section is easily transferred to the feeding section, causing the pellets in the cup to soften and stick, resulting in bridging, which has a serious impact on the stable supply of consumables. In addition, due to the small volume of the printing material cup, manual feeding is required when printing large products, which results in a low level of automation and a waste of manpower. Therefore, it is necessary to develop an automatic feeding device to meet actual needs.

Figure 3.42 shows the design and physical drawings of the automatic feeding device. The storage cup can be filled with 2L plastic pellets to meet the continuous printing of products above 1.5 kg. The size of the printing material cup is small. Its structure ensures that the consumables are not easy to bridge, and the conveying is stable. Use KEYENCE LR-T series laser sensor to detect the height of the liquid level in the printing material cup by means of triangular distance measurement. The pneumatic valve uses SMC pneumatic single-axis cylinder, and pushes the consumables in the storage cup to the printing material cup through the push rod.

When the liquid level in the printing material cup is lower than the preset value, the laser sensor sends a signal to the consumable detection device of the control unit. After the judgment, the execution signal is sent to the pneumatic valve. The pneumatic valve pushes the cylinder rod to quantitatively push the pellets in the storage cup to the printing cup. Until the preset liquid level is reached, the pneumatic valve stops working to ensure a stable supply of consumables for a long time and avoid bridging caused by accumulation of the printing material cup.

- ② *Design of Melting and Plasticizing Device* The design of the micro screw determines the stability and controllability of the melt extrusion flow. Due to the overall size of the equipment, the length of the miniature screw is 150 mm, the outer diameter of the screw is 12 mm, the ratio of length to diameter is 10:1, the width of the screw groove is 10 mm, and the width of the screw edge is 1.5 mm. In order to ensure that the pellets can be fed into the barrel stably, the groove depth



1—storage cup; 2—printing cup; 3—pneumatic valve; 4—laser sensor

Fig. 3.42 Design drawing and device drawing of automatic feeding device

of the feeding section is 2 mm, and the length distribution of the feeding section, compression section, and metering section is 20%, 30%, and 50%, respectively.

According to the previous theoretical analysis of the micro-screw, in order to reduce the drag flow's influence on the melt extrusion flow, comprehensively considering the aspect ratio and the extrusion flow rate, the helix lift angle is determined to be 17.4° . In order to reduce leakage, the screw edge width e is selected slightly larger, and the ratio of the screw edge width to the outer diameter of the screw is 0.15. The ratio of the depth of the groove in the metering section to the outer diameter of the screw is 0.1. Figure 3.43 is a schematic diagram of the micro screw.

The gap between the screw and the barrel is 0.1 mm. Because the screw bears the combined action of torsion and compression, the material requirements of the screw are relatively high. To maintain mechanical properties at high temperatures, as well as the original higher strength and dimensional stability, the micro-screw adopts nitride 38CrMoAl alloy steel. Its mechanical properties are relatively excellent, and the thickness of the nitride layer is 0.3–0.7 mm.



Fig. 3.43 Physical picture of micro screw

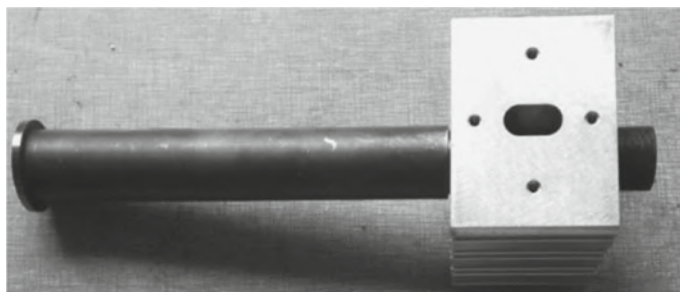


Fig. 3.44 Machine barrel physical map

The barrel also uses 38CrMoAl alloy steel. The heat dissipation groove is processed at the feeding place, and the temperature is cooled by air cooling to reduce the risk of pellet bridging. Figure 3.44 are the physical drawings of the barrel.

The driving motor is 57 stepper motor, and its maximum output torque is 3.0 Nm. Equipped with a 1:5 planetary reducer, the theoretical maximum torque can reach 15 Nm, which can meet the extrusion requirements.

(2) Design of on-demand extrusion device

According to the different driving methods, there are two types: electromagnetic and pneumatic. Among them, the electromagnetic type uses the electromagnet to push the valve needle to produce reciprocating motion, and its holding force is 10kgf (1kgf = 9.8 N). The main body of the device and the electromagnet are connected to the flow channel plate through the bolts, so that the electromagnet maintains high stability during the high-frequency reciprocating movement of the valve needle, and at the same time maintains the stability when the valve needle impacts the nozzle. Because the electromagnet and the runner plate are connected by only four bolts, it is point contact, and the rest of the structure is placed in the air, which ensures the timely heat dissipation of the electromagnet and the minimum heat transfer of the hot runner to the electromagnet. Figure 3.45 shows the electromagnetic on-demand extrusion device.

Among them, the pneumatic on-demand extrusion device realizes the on-demand extrusion of the melt by modifying the MAC pneumatic valve and improving the NORSON hot melt glue machine. It can satisfy the extrusion of melt below 260 °C. The reciprocating frequency of the valve needle can be as fast as 5000 Hz, which meets the requirements of use. Figure 3.46 shows the pneumatic on-demand extrusion device.

The nozzle diameter of the device is 0.2 mm, and it is processed by EDM. Its microstructure is shown in Fig. 3.47. The surface is coated with a Teflon coating to reduce the adhesion between the melt and the nozzle and reduce the overheating decomposition phenomenon caused by the excessive adhesion of the melt to the nozzle.

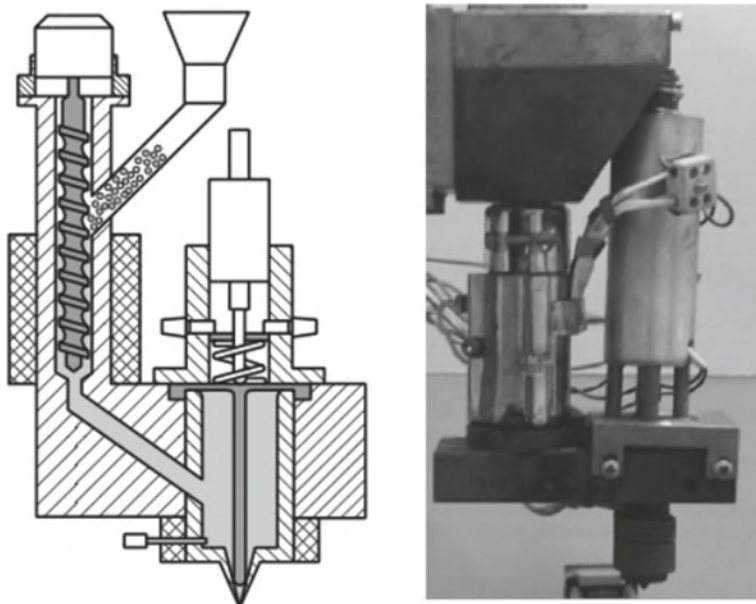


Fig. 3.45 Electromagnetic on-demand extrusion device

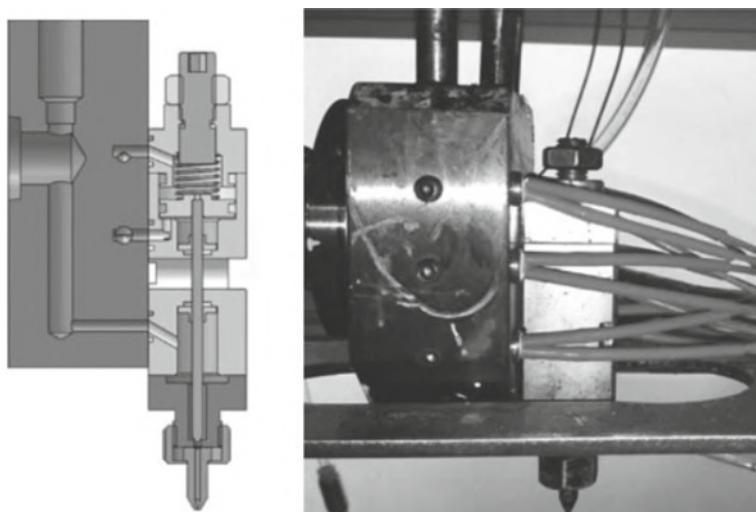
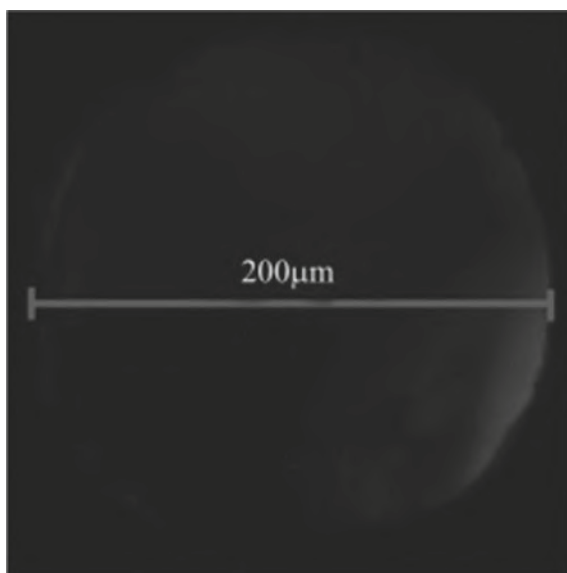


Fig. 3.46 Pneumatic on-demand extrusion device

Fig. 3.47 Microstructure of nozzle bore



(3) Design of accumulation forming device

The overall structure of the melting and plasticizing device and the on-demand extruding device is heavier than the three-dimensional motion platform. In addition, the melting and plasticizing section and the on-demand extrusion section are connected as a whole, and the overall size is relatively large. If the traditional fused deposition forming device is used, that is, the way of printing products through the nozzle moving in the X–Y axis direction and the moving platform moving in the vertical direction of the Z axis has the following shortcomings. Due to the larger mass of the integral consumables extrusion system, the inertia is larger. It is impossible to achieve fast and accurate on-demand extrusion. As a result, the printing speed is reduced and the machine head vibrates obviously. And there are problems such as low printing accuracy. In order to avoid the above problems, the movement platform is used to move as a whole in the three directions of X–Y–Z axis, and the on-demand extrusion system is fixed on the top of the movement platform as a whole.

The accumulation forming device includes a printing platform and a three-dimensional motion module. The three-position motion module adopts the CCM-W50-50 kg-level linear slide module, which is driven by 42 stepping motors with an accuracy of 0.05 mm. The maximum load is 50 kg. X-axis adopts 2 groups, Y-axis adopts 1 group, and Z-axis adopts 4 groups for combined installation to meet the requirements of three-dimensional motion. As shown in Fig. 3.48.

The printing platform consists of two parts: a glass plate and a heating plate. By heating the heating plate, the platform can be heated to a maximum of 100 °C, which

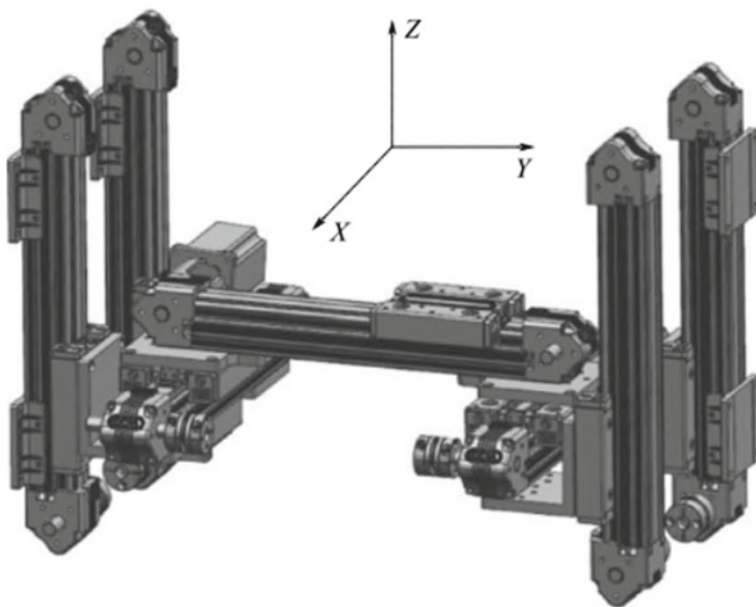


Fig. 3.48 Three-dimensional motion module combination method

can alleviate the phenomenon of melt cooling shrinkage. The maximum print size is $300\text{ mm} \times 300\text{ mm} \times 300\text{ mm}$.

(4) Equipment control unit

The equipment control unit includes three-dimensional motion control, temperature control, pressure control and feed control. Among them, the temperature control adopts PID control method, and the FX3U series PLC is used to control the temperature within the allowable range in time. Temperature control is divided into barrel temperature control and motion platform temperature control. The temperature of these areas is converted into an electrical signal by thermocouple detection, and compared with the electrical signal of the temperature setting value, and the temperature is stabilized by setting the appropriate PID parameters.

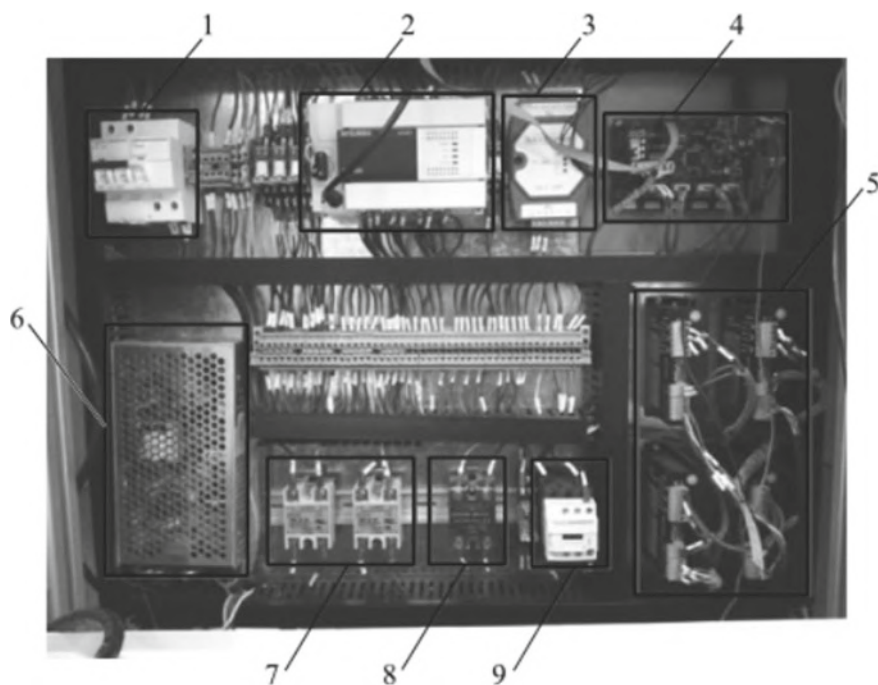
In addition, the opening and closing of the valve needle is realized by an isolated signal converter. Convert the stop and discharge DC current signal output by the motion control main board into a proportional output DC current or voltage signal isolated from the input signal, and transmit it to the solenoid valve to control the opening and closing of the needle valve.

In the process of melt extrusion, the flow rate needs to be kept stable. Therefore, the melt pressure needs to be stable. The application of pressure closed-loop control device can more accurately control the melt extrusion pressure. The pressure closed-loop control device selects PT124 type, the range is $0\text{--}25\text{ MPa}$, and the diaphragm temperature resistance is $400\text{ }^{\circ}\text{C}$. Among them, the feed control is as mentioned above, the analog current signal of the laser sensor is read into the PLC analog

quantity unit, the calculation is performed, and the movement of the pneumatic valve is judged. Figure 3.49 shows the control module of the melt differential 3D printing equipment. Figure 3.50 is the control interface, which is used to display and adjust various control parameters.

According to the basic process of 3D printing, the 3D model is converted into a path file by the slicing software, and then input into the 3D printing control system for printing. For the melt forming process, the Arduino motion control board is commonly used for related signal monitoring and motion drive.

In this section, the open-source 3D printing control motherboard MKS-Gen V1.3 is used for 3D motion control. It integrates all circuit interfaces required for three-dimensional motion control on a small-size circuit board, such as stepper motor drive interface, travel fiber switch interface, etc. As shown in Fig. 3.51. The MKS-Gen V1.3 control board adopts Marlin firmware settings. It can read the model digital file generated by the slicing software. And it can set the platform movement speed and printing range. At the same time, it has the functions of high-speed printing, power-off printing, acceleration control and so on. Because the mainboard current is



1-master switch; 2-FX3U series PLC; 3-isolated signal converter; 4-motion control main board;
5-motion driver; 6-24V power supply; 7-cylinder heating temperature control relay;
8-substrate heating temperature control relay; 9-Tesys contactor

Fig. 3.49 Melt differential 3D printing equipment control module

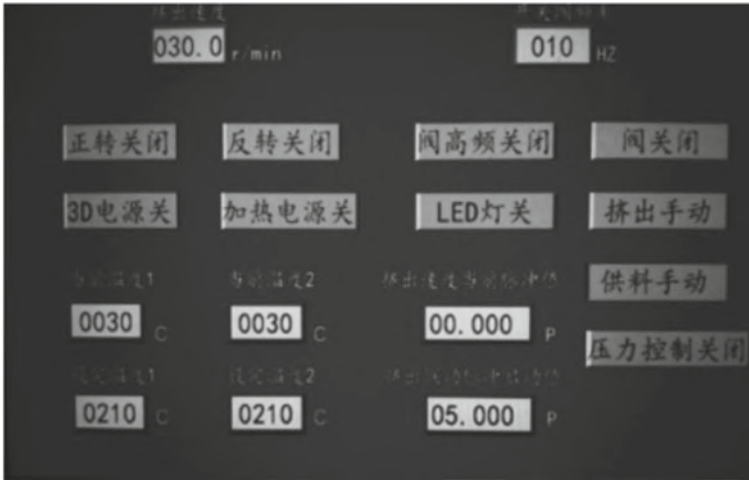


Fig. 3.50 Melt differential 3D printing equipment control interface

difficult to directly drive the stepper motor of the 3D motion module, it is necessary to increase the stepper motor driver separately. The main board transmits the signal to the driver, and then realizes the movement of the three-dimensional motion module.

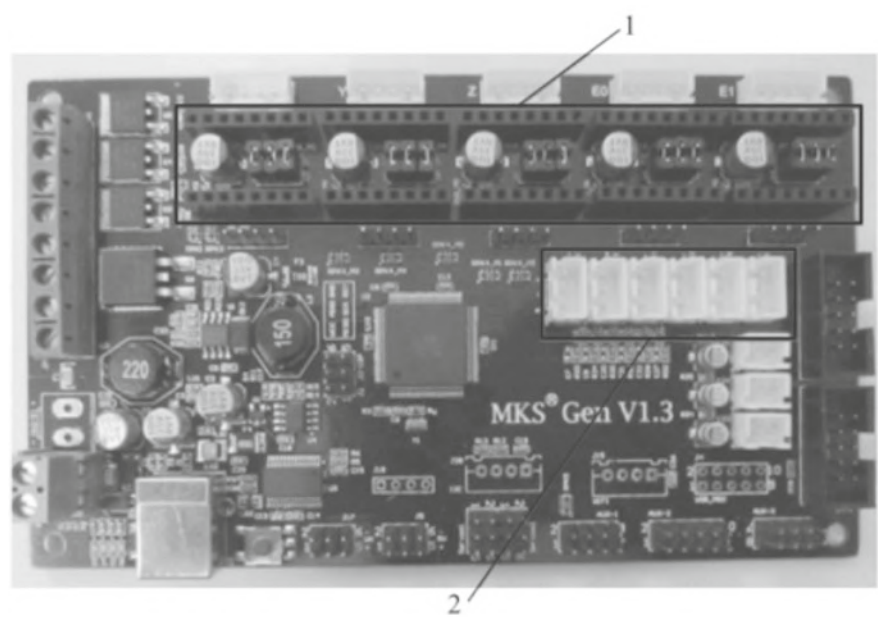
In addition, in order to realize the unified operation of three-dimensional motion and melt extrusion, the MKS-Gen V1.3 control mainboard simultaneously controls the motion of the screw drive motor. Through the construction of plug-ins, the matching of platform movement speed and screw rotation speed can be realized to meet the precise control of melt extrusion.

3.2.5 Industrial-Grade Melt Differential 3D Printer

(1) Theoretical analysis of accumulation process

According to the research of Jin [60], the cross section of the extruded fuse is regarded as a combination of a rectangle and two semicircles (Fig. 3.52). During the fuse stacking process, the distance between the fuses determines the accuracy and strength of the product. Therefore, it is very important to determine the relationship between fuse spacing and related process parameters. According to formula (3.22), it can be obtained that the fuse distance is proportional to the flow rate Q , and inversely proportional to the printing speed v and the layer height h . Therefore, it is necessary to accurately measure the flow rate under different process conditions, and determine the appropriate fuse spacing through coordination with speed and layer height.

$$\varepsilon = \omega - \Delta c = \frac{Q}{vh} \quad (3.22)$$



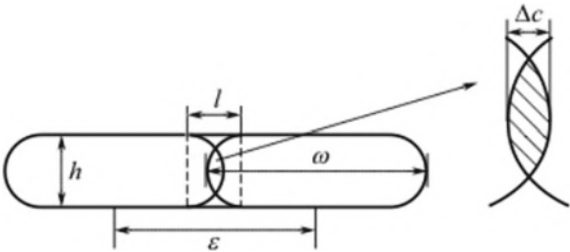
1-motion drive interface; 2-stroke limit interface

Fig. 3.51 Melt differential 3D printing motion control motherboard

In the formula, ε is the fuse spacing; ω is the fuse width; Δc is the intersection width of the fuse.

According to formula (3.11), there are three factors that affect the melt flow. One is the geometry of the nozzle, which is proportional to the 4th power of the nozzle diameter and inversely proportional to the length of the nozzle. The second is the pressure difference between the inside and outside of the nozzle, which is caused by the back pressure caused by the rotation speed of the screw. The third is the viscosity of the melt. As a non-Newtonian fluid, its viscosity is greatly affected by temperature. When the temperature is lower, the viscosity is high, and higher pressure is required to extrude the nozzle. Therefore, when the nozzle diameter and length have been

Fig. 3.52 Schematic diagram of extrusion micro-unit stacking



determined, the flow can be adjusted by changing the extrusion pressure and melting temperature.

(2) Design of industrial grade melt differential 3D printer

Based on the analysis of the pellet 3D printing device, the pellet 3D printing device has the following shortcomings. Material transportation is unstable, such as bridging, uneven particle size, etc. It is easy to mix in air during the plasticizing process. The salivation of the nozzle is uncontrollable. The plasticized structure is bulky and so on. The above-mentioned problems limit the use of granular 3D printers, so solving the above-mentioned problems becomes the key.

In this section, the melt differential 3D printing device is modified, and the valve control system is converted to a pellet extrusion system using a two-stage screw extrusion mechanism. The first-stage screw has a large diameter, which is used for conveying and melting, and provides pressure. The second-stage screw has a small diameter and is further plasticized and measured. At the same time, there is a vent hole at the joint position, which has a good venting effect and avoids air bubbles when the fuse is extruded.

Based on the above principles, a set of experimental system is designed. The 3D printing device system based on the melted accumulation of pellets is shown in Fig. 3.53. It includes a melt generating unit, a three-dimensional stacking unit and a process control unit. The melt generating unit includes a melting pressure building unit and a plasticizing metering unit. Among them, the melting pressure building unit is mainly used to convert plastic pellets into melt and build pressure. It contains the melting and pressure building section. The motor drives the screw to rotate in the barrel, and the heating jacket is fixed on the barrel. The plastic pellets are melted by the heat generated by the heating jacket, and are transported to the front end by the rotation of the screw. Since the depth of the screw groove at the front end of the screw is smaller than that at the rear end, a large and stable pressure is established. At the same time, in the plasticizing metering unit, another driving motor drives the metering screw to rotate, and the melt delivered from the melting and pressure building section is extruded into the three-dimensional stacking unit through the nozzle as required.

According to the processing principle, a melt differential 3D printer with a two-stage screw mechanism is prepared. Figure 3.54 shows the physical picture of the device. Among them, the hopper is 30 L, which ensures that one feed can meet the printing time of more than 3 h. The diameter of the first stage screw is 25 mm, the ratio of length to diameter is 20:1, and the maximum speed of 100r/min can be achieved. The second section of the screw has a diameter of 16 mm and a length-to-diameter ratio of 6:1. It can achieve a maximum speed of 120r/min and realize forward and reverse rotation through pulse signals. Install a pressure sensor at the junction of the two screws. The speed is interlocked by the pressure and the first-stage screw extrusion. According to the pressure level, increase or decrease the screw speed to ensure the pressure stability. The inner diameter of the nozzle is 4 mm, and the outer diameter is 8 mm, ensuring fast printing of products.

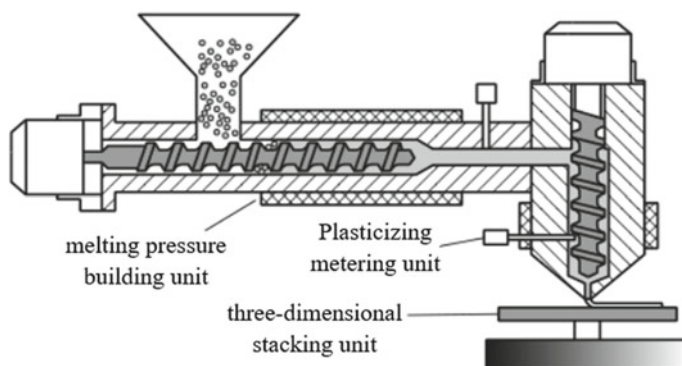
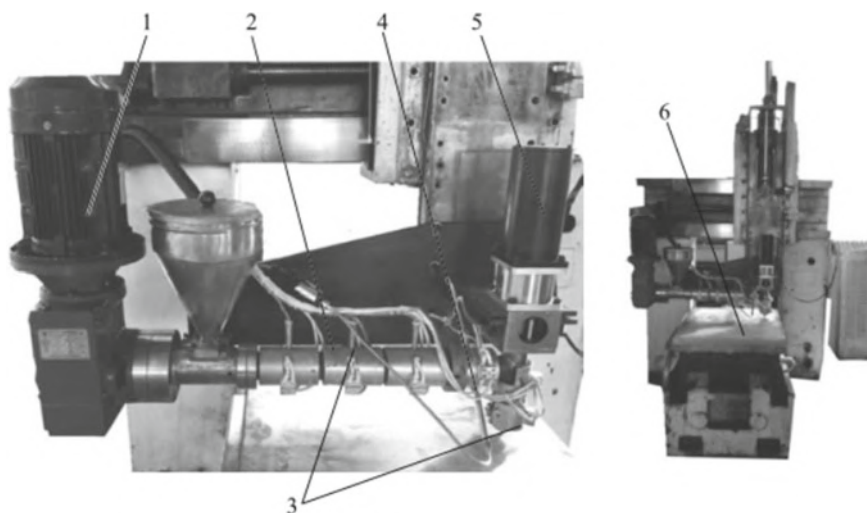


Fig. 3.53 3D printing device system based on melted accumulation of pellets



1-first-order motor; 2-heating coil; 3-temperature sensor;
4-pressure sensor; 5-second-order motor; 6-three-dimensional motion platform

Fig. 3.54 Industrial grade melt differential 3D printer

The three-dimensional motion platform is modified with a vertical milling machine motion platform. The extrusion equipment is fixed on the Z-axis vertical movement axis, and the movement platform can move along the X and Y directions. The printing area is 800 mm × 600 mm × 600 mm, and the surface of the platform can be heated up to 120 °C.

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Chapter 4

Polymeric 3D Copiers

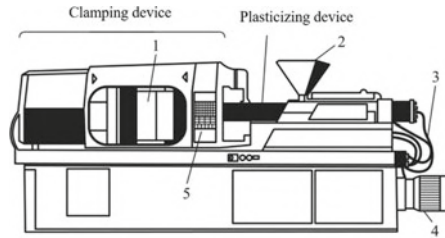


4.1 Overview

The most typical 3D photocopier is injection molding machine (referred to as injection machine), as shown in Fig. 4.1. It is a kind of high-pressure plastic melt at high-speed injection has been closed. It is a kind of molding equipment that, within high speed and high pressure, the plastic melt is injected into the closed mold cavity, and the plastic products consistent with the mold cavity are obtained after cooling and shaping. Under the premise that the specific shape of the product is known, the corresponding mold is processed, so that the product with the same shape and size as the given product can be made in large quantities. It means it has the property of “copying”. Therefore, it can also be called the injection molding machine as the 3D copier of polymer products. It has the following features: with a molding getting the plastic products with complex shape, precise size or insert can be obtained; gaining strong adaptability to all kinds of plastic processing; obtaining high productivity and easy to realize automatic production machine. So, the injection molding technology and injection molding machine (also known as injection machine) is widely used, and has now become a plastic processing and plastic machinery industry. Injection molding machine utilization rate accounts for more than 50% of the whole plastic molding machinery.

With the continuous development of science and technology and the proposal of industry 4.0, the injection molding machine is developing in the direction of “precision, energy saving, high efficiency and integration”. General injection molding machine continuously pursue the perfection of injection molding machine. With the goal of rapid and efficient (shorten the molding cycle), large-scale production, energy saving, manufacturing more and more complex products, the goal of “forming as assembly, forming as use” is realized. As injection molding system has become a more and more integrated machine system, injection molding process and injection molding machine have become a part of the system. And more application technologies are integrated and innovated into injection molding machine. Automated parts

Fig. 4.1 Typical injection molding machine



1 - mold; 2 - hopper; 3 - hydraulic pipeline; 4 - motor; 5 - control panel

extraction, assembly, packaging, inspection and other components are configured. Big data and Internet technology are used to realize the physical linkage collaboration and more intelligent man–machine interaction between injection molding machines.

4.2 Components and Classification of 3D Copiers

4.2.1 Components of a 3D Copier

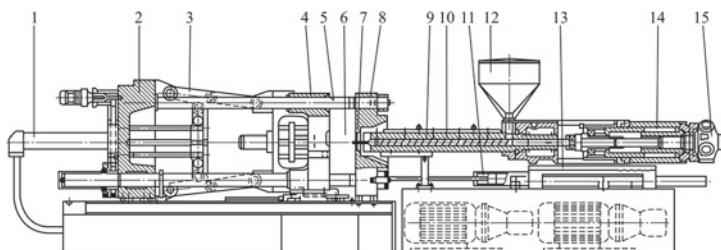
The structure of the 3D copy machine is shown in Fig. 4.2. It is mainly composed of injection system, clamping system, transmission system, heating and cooling system, electrical control system, lubrication system, etc.

(1) Injection system

Injection system of injection molding machine is the core of polymer melting plasticization, which directly determines the homogeneity of plastic melting and the quality of products. Injection system is mainly divided into three types: plunger type, screw type and screw pre-plastic plunger injection type. Screw type is the most widely used at present. Its function is, after heating and plasticizing a certain amount of plastic in an injection cycle, to inject molten plastic into the mold cavity by screw under given pressure and speed. After the injection, the melt injected into the cavity is held in shape. It mainly includes the hopper, injection screw, barrel, nozzle and other components, as shown in Fig. 4.3.

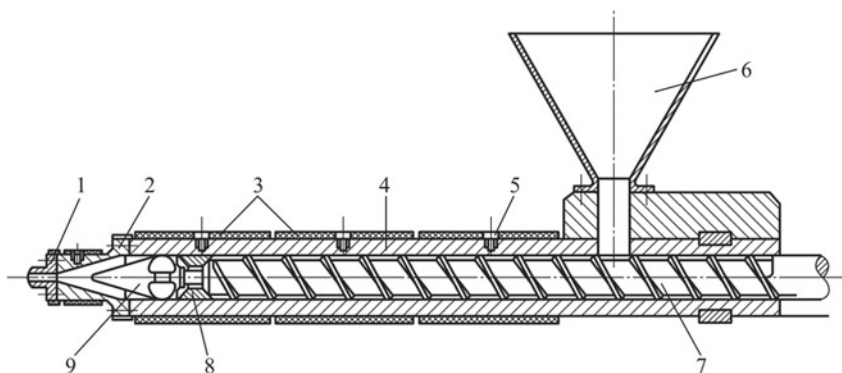
(2) Clamping system

Clamping system is the part that determines the shape of the product. It is the place where the molten material is finally formed. Its main function is to ensure that the mold can be opened and closed reliably and eject the product, so its quality has a significant impact on the dimensional accuracy of the product. The mold system is mainly composed of mold opening and closing mechanism, pull rod, mold adjusting mechanism, ejection mechanism, fixed template and safety protection mechanism. Its structural form is mainly divided into two plates type and three plates type, as shown in Fig. 4.4.



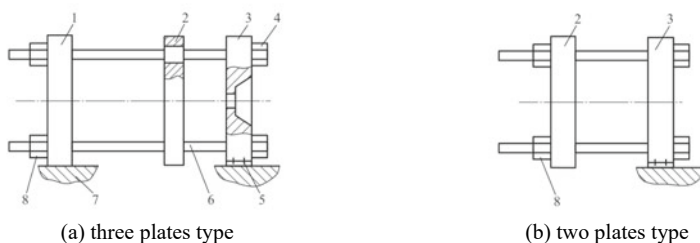
1- toggle locking cylinder; 2 - after fixing template; 3 - toggle; 4- movable template; 5 - pull rod; 6 - capacity space; 7 - nozzle; 8 - front fixed template; 9 - screw; 10 - base; 11 - injection device traction cylinder; 12 - hopper; 13 - injection device guide; 14 - injection cylinder; 15 - screw rotary drive

Fig. 4.2 3D photocopy structure (without control system)



1 - nozzle injection molding machine injection system; 2 - barrel head; 3- heating coil; 4 - barrel; 5 - thermocouple; 6 - feed hopper; 7 - reciprocating; 8 - check valve; 9 - screw head

Fig. 4.3 Injection system of injection molding machine



(a) three plates type

(b) two plates type

1- after fixed template; 2 - movable template; 3 - before the fixed template; 4 - before the nut; 5 - set screw; 6 - pull rod; 7 - frame; 8 - rear nut

Fig. 4.4 Basic form of clamping system

(3) Transmission system

From the working process of the injection molding machine, the transmission system is mainly reflected in five places: the opening and closing of the mold, the ejection of the product, the rotation of the screw, the axial movement of the screw, and the overall movement of the injection system or the mold system. With the continuous development and application of new technology, the transmission system of injection molding machine is no longer limited to hydraulic type, a large number of fully electric equipment have been developed. On this basis, the injection molding machine drive system can be divided into hydraulic transmission system and fully electric drive system. Hydraulic transmission system has a series of advantages, such as high precision of mold closing, large opening and closing force, easy to realize the process of pressure and velocity control and centralized control of the machine. Hydraulic drive system consists of hydraulic pump, hydraulic motor, all kinds of valve, piston, and other hydraulic components, and its transmission relies on the hydraulic pressure. Two direct compression plate type is representative of this kind of structure. Hydraulic clamping mechanism of two direct compression plate can be divided into non circulation type, external circulation type and internal circulation type, as shown in Fig. 4.5.

Fully electric drive system does not include any hydraulic components. Specific to the injection molding machine, its main difference from the hydraulic transmission system is that the mold is opened and closed, the movement of the injection screw does not utilize hydraulic pressure, and the rear end of the injection screw does not have to use the structure of the injection cylinder. Fully electric drive system is mainly composed of motor, gear, ball screw transmission parts, etc. At present, fully electric injection molding machine mainly uses the servo motor to replace the original oil cylinder to push the elbow bar to open and close the mold. Therefore, the existing problems of the original elbow bar machine continue to exist, such as high machining accuracy, easy to wear, mold adjusting difficulty. But some aspects have also been improved, such as energy saving, high control precision and repeatability, high efficiency and environmental protection. With the expansion of the application scope and demand of high-precision thin-wall injection molding parts, as well as the increasing awareness of environmental protection, the electric toggle clamping mechanism has been recognized by people for its advantages. At present, fully electric injection molding machines produced by major injection molding machine manufacturers in the world adopt this clamping mechanism.

Of course, there is also an electric direct pressing clamping mechanism. According to the forward and reverse rotation and speed of the servo motor, the clamping mechanism realizes the opening and closing movement and speed switching of the mold through the ball screw pair. After the mold contacts, the thrust is generated according to the torque output by the servo motor to realize the mode locking. This clamping mechanism system has the advantages of high rigidity, high transmission accuracy, high efficiency and energy saving, but there is no force increasing mechanism when locking the mold. The axial force of ball screw is large, and the mechanical wear is serious, so it is only suitable for micro machine.

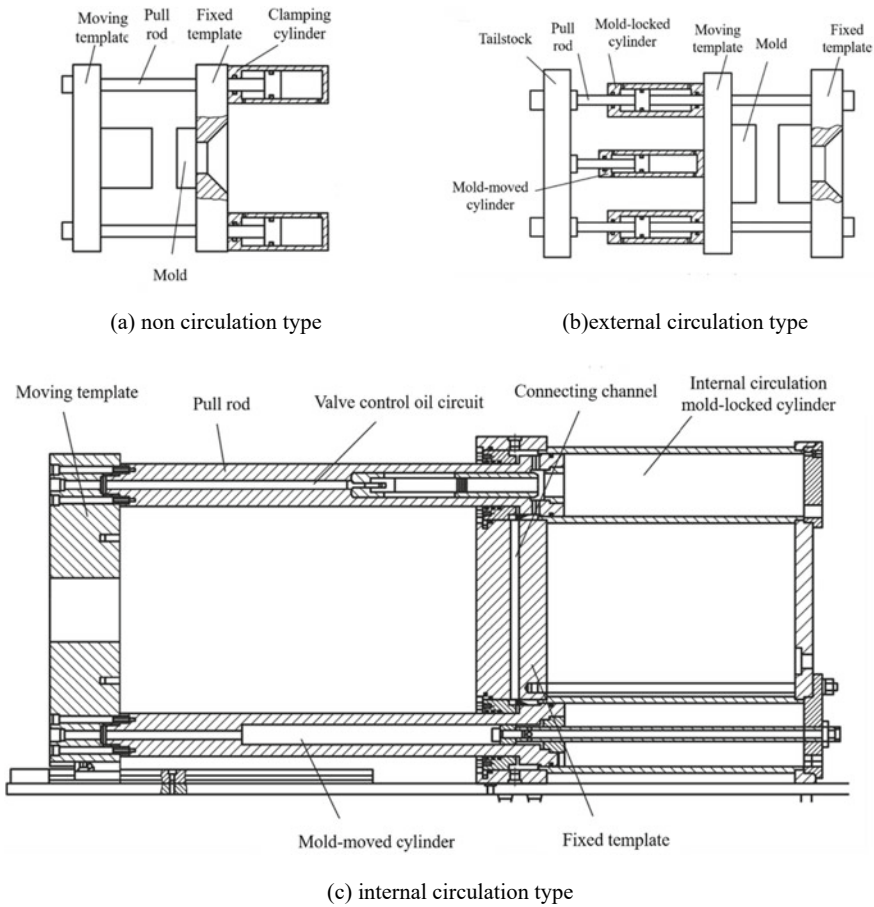


Fig. 4.5 Hydraulic clamping mechanism of two direct compression plate

The structure of the electric composite mechanism is shown in Fig. 4.6.

Hydraulic and electric transmission systems have their own advantages and disadvantages. At present, fully electric injection molding machines are mainly used for small and medium-sized injection molding machines to produce high-grade precision and small precision parts, while different types of all hydraulic injection molding machines are used for the molding of high-grade, high-grade precision and large products [1]. "Minicomputer electrification, mainframe two board" has become a development trend.

(4) Heating and cooling system

The heating system of the copier is used to heat the cylinder and injection nozzle. The injection molding cylinder usually uses the electric heating ring as the heating device, which is installed outside the cylinder and tested by the thermocouple in

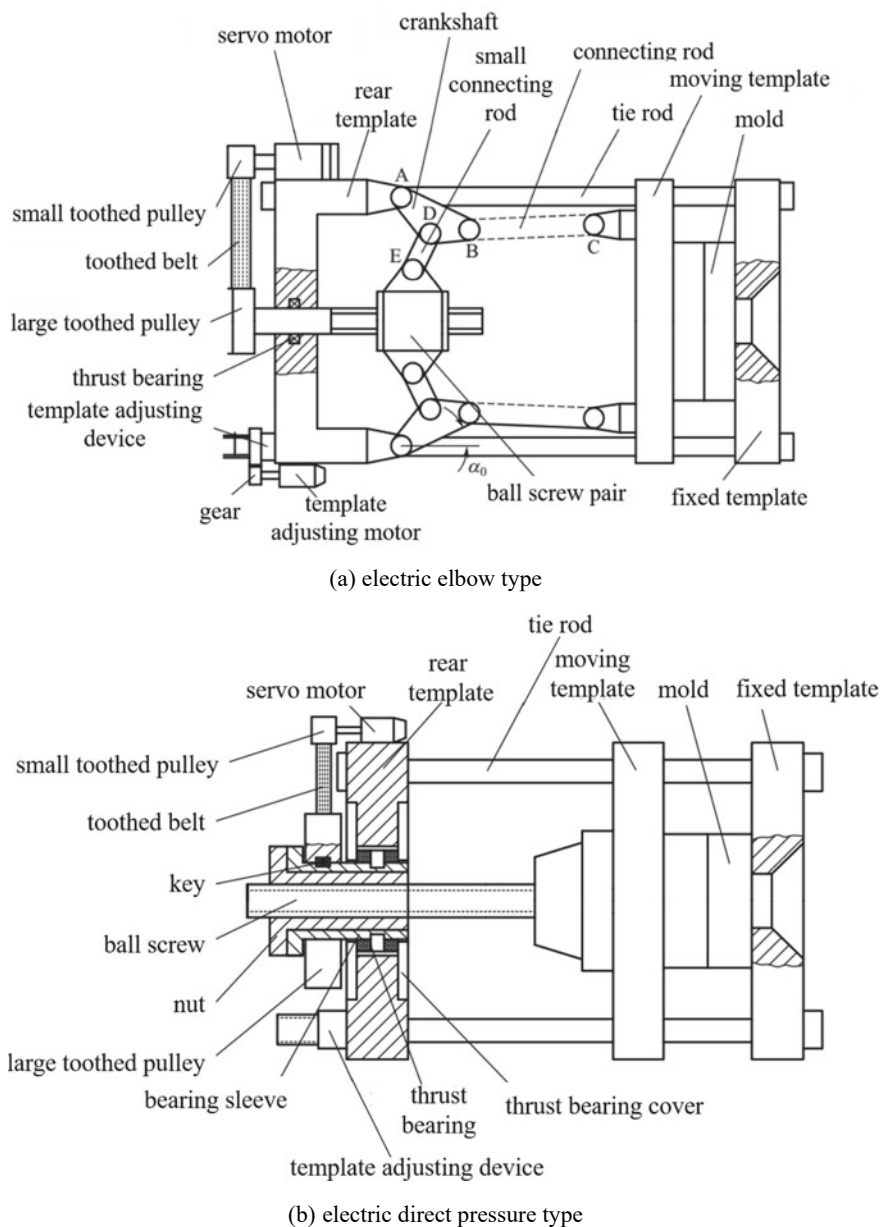


Fig. 4.6 Electric clamping mechanism

sections. Heat conducts through the cylinder wall to provide heat source for material plasticization. Cooling system is mainly used to cool the oil temperature. Excessive oil temperature will cause many faults, so the oil temperature must be controlled. The other place to be cooled is near the discharge port of the hopper, which prevents the raw material from melting at the discharge port, leading to bridging so that the raw material can not be discharged normally.

(5) Electrical control system

Electrical control system controls and adjusts the whole injection process. It needs to ensure that the injection machine runs correctly according to the set process conditions (pressure, temperature, speed, time) and sequence of operation. It mainly includes electrical appliances, electronic components, meters, sensors, etc. Electrical control generally has four control modes: manual, semi-automatic, automatic and adjustment.

(6) Lubrication system

The lubrication system mainly provides certain lubrication for the relative moving parts of the injection machine, such as the movable template, the adjusting device, the pull rod, the injection base, etc., in order to reduce the energy consumption and improve the service life of the parts. The lubrication can be either regular manual lubrication or automatic electric lubrication.

(7) Safety system and auxiliary system

The function of safety system is to ensure the safety of operators and equipment. It is mainly composed of various safety valves, safety doors, photoelectric detection elements, limit switches, etc. Now the injection machine can achieve multiple safety protection.

Auxiliary system includes: drying device, mixing device, crushing device, feeding device and temperature controller, auxiliary device for mold installation and mechanical hand, etc.

4.2.2 Classification of 3D Copiers

Injection molding machines can be classified into plunger and screw molding machines according to their plasticizing methods. According to its structural form, it can be divided into vertical injection machine, horizontal injection machine, angle injection machine and combination injection machine. It can be divided into electric type and hydraulic type according to driving type. According to the closing mechanism, it can be divided into three-plate type and two-plate type. It can be divided into rod-type injection machine and rod-free injection machine according to whether or not the rod is present. It can be divided into thermoplastic injection molding machine, thermosetting plastic injection machine, low foaming injection machine, multi-component injection molding machine, two-color/mixed-color injection molding machine, etc.

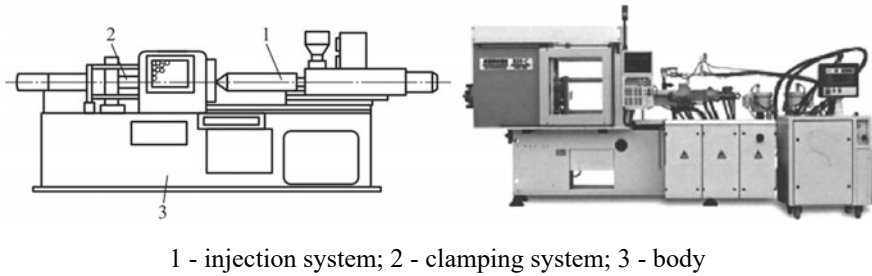


Fig. 4.7 Horizontal injection molding machine

At present, more classification methods are used in the industry as follows.

(1) Classified by structure

The structural form refers to the relative position of the center axis of the injection screw and the direction line of the opening and closing mode of the mold system. The horizontal position of both is called the horizontal type and the vertical position is called the vertical type.

① Horizontal type

Horizontal injection molding machine is the most widely used and most basic form at present. Its structure is shown in Fig. 4.7. It is suitable for the production of various batches of products. Its screw axis and opening and closing direction are arranged horizontally. Due to the structural characteristics of the horizontal injection machine, it has the following advantages: low body, stable, easy operation and maintenance. Products can be easily automated by using their own weight to fall off.

② Vertical type

The screw axis and opening and closing direction of the vertical injection machine are perpendicular to the ground, and its structure is shown in Fig. 4.8. It covers a relatively small area, but because the equipment is arranged along the height direction and occupies a large space in the height direction, the vertical injection molding machines are mostly small equipment. Moreover, the center of gravity of the vertical injection molding machines is relatively high, and the stability is not as good as that of the horizontal ones, so the way to take out the products also makes the implementation of automation more difficult. Therefore, the application scope of the vertical injection molding machines is relatively narrow.

③ Angular

Angular injection machine is shown in Fig. 4.9. The screw axis is perpendicular to the direction of opening and closing mold. Most of the arrangements are horizontal screw arrangement and the opening and closing mold direction is perpendicular to the

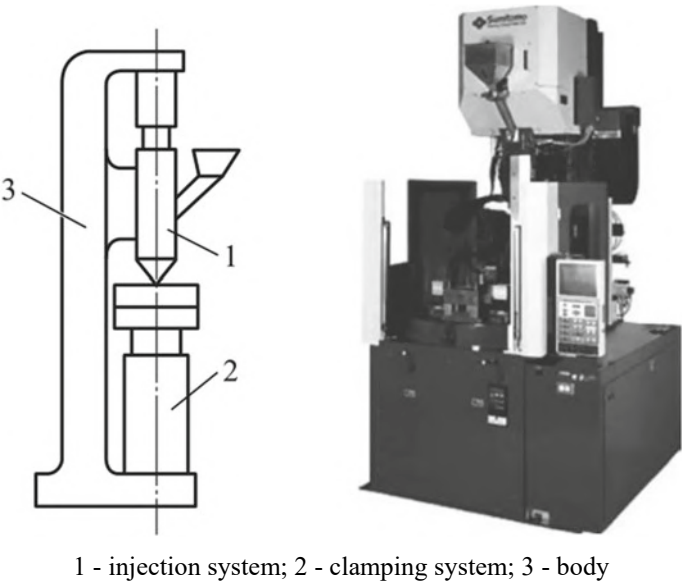


Fig. 4.8 Vertical 3D photocopier

ground. Angular 3D photocopier combines the advantages of horizontal and vertical copiers, and is also commonly used. It is especially suitable for products where no gate marks are allowed in the forming center.

(2) Classification by machining capacity

The parameters often used to indicate the processing capacity of injection molding machine include the injection volume and clamping force of the machine. Most of them are expressed by injection volume and clamping force at the same time. The classification is shown in Table 4.1.

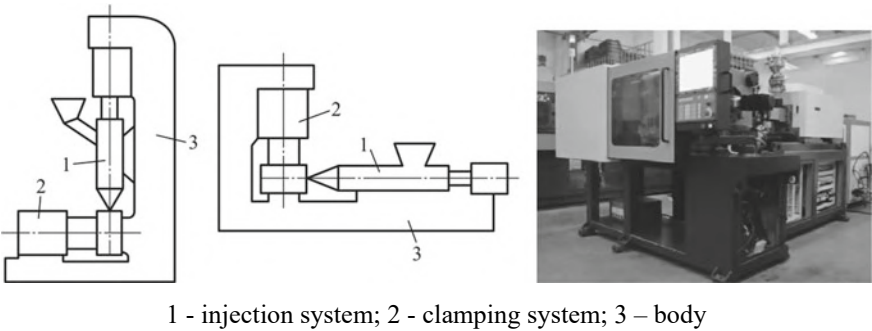


Fig. 4.9 Angular 3D photocopier

Table 4.1 Classification range by machining capacity

Category	Clamping force/kN	Injection volume/cm ³
Subminisize	< 200~400	< 30
Small-size	400~2000	60~500
Middle-size	3000~6000	500~2000
Large-size	8000~20,000	> 2000
Supersize	> 20,000	

The injection volume only specifies the weight range of the machine molded products, while the clamping force is limited from the area of the molded products. However, in the actual processing of products, there is no strict proportional relationship between the two. With the expansion of the scope of processing plastic products, the contradiction is greater. For instance, in the molding plate, basin, frame and other products, the molding area of the machine is the main, while the injection volume of the machine is often insufficient. Therefore, in order to design and use the machine more reasonably, at present, the injection and clamping devices are standardized (building block type) in some manufacturing plants. In this way, less design can be used to meet the requirements of a wide range of use.

(3) Classification by use

Injection molding has a wide range of applications. In order to meet the requirements of various injection processes and improve the mechanical efficiency, the machine is designed to be thermoplastic universal type (also known as ordinary type), thermosetting type, exhaust type, high-speed type, multicolor, precision type, shoe type, threaded products type, etc. Among them, thermoplastic universal series, thermosetting series, low foaming series, exhaust series and high-speed series are the most common.

① Thermosetting plastic injection molding machine

The traditional molding process of thermosetting plastics includes compression molding and transfer molding. Both methods have some disadvantages, such as complex operation, long molding cycle and low production efficiency. With the progress of technology and the urgent need of production efficiency, the injection molding technology of thermosetting plastics has been well developed. The principle of thermosetting injection molding is the same as that of thermoplastic injection molding. The injection material is heated by the external heating of the barrel and the shearing heat of the screw. And then it is preheated and plasticized in the barrel with low temperature, so that the resin changes physically and chemically slowly to form a thick gel and produce fluidity. The screw or plunger is used to inject it into the mold under strong pressure, and the chemical reaction is carried out under high temperature and high pressure. After a period of pressure maintaining, the product is solidified and finally taken out [2]. The differences between thermosetting injection molding and thermoplastic injection molding are shown in Table 4.2.

Table 4.2 Differences between injection molding process of thermosetting and thermoplastic [3]

Classification	Thermosetting plastic	Thermoplastic plastic
Temperature of barrel	Below 5 °C; can not be injected at too low temperature; will occur curing at too high temperature, strict temperature control; enable to use water jacket for temperature controlling	Above 150 °C; can not melt at too low temperature; will affect the injection, and even cause degradation at too high temperature; the temperature control is not strict
Control of injection volume	After each injection, should make the front barrel expect little; to prevent hardening plug nozzle	After each injection, a considerable amount of anticipation should be made at the front of the barrel to compensate
Temperature of mold	Generally above 170 °C; the curing time will be longer at too low temperature; will be too fast at too high temperature; the cavity cannot be filled	Below 100 °C or even cooled by cooling water
Change attribute	Physical chemical changes; after injection into the cavity, the chemical reaction will decompose the gas	Physical change; no decomposition gas

Thermosetting plastic injection molding machine is divided into plunger type and screw type in two forms. Plunger type injection molding machine is mainly used in bulk molding compounds (BMC), screw injection molding machine is mainly used for thermosetting phenolic injection plastics [4]. The thermosetting plastic injection machine has the same structure as thermoplastics, but its parameters are controlled more strictly. The design requirements are as follows:

- Good feeding characteristics (compact BMC plastics must be equipped with extruded hoppers or automatic feeders).
- Ensure that the plastic is heated evenly in the barrel and eliminate the influence of excessive friction heat on the plastic.
- Higher efficiency is achieved by the large number of plastics and plasticizers passing through the nozzles.
- Prevents plastic from curing in the barrel or head.
- High locking force.
- Proper clearance between screw and barrel.
- The heating part of the barrel shall have a cooling device to strictly control the temperature.

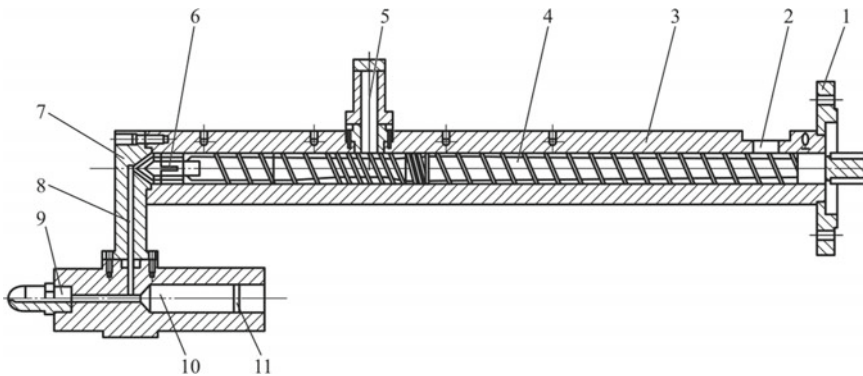
② Exhaust injection machine

In polymer injection molding, because some materials (such as ABS, PA, etc.) contain lots of water, gases or volatile components, a series of pretreatments such as drying before injection are often required. therefore, additional pretreatment equipment is needed. If this pretreatment process can be completed in the injection machine, labor

and material resources will be greatly saved. Exhaust injection machine was put forward under this background.

Figure 4.10 shows the structure of an exhaust injection machine, which consists of a plasticizing system and a storage injection system, and both of them are distributed in parallel. There is a connecting sleeve between the two parts, in which there is a flow channel. Due to the parallel distribution of the plasticizing system and the charge injection system, the exhaust screw only acts as a plasticizer when working, without axial displacement, while the injection task is performed by the charge injection system. When working, the material is added from the hopper and transferred to the barrel through the metering and feeding device. Material is basically in a molten state after being conveyed in the first screw feeding section, mixing and melting in the first compression section and homogenizing in the first metering section. When entering the exhaust section, due to the abrupt deepening of the groove in the exhaust section, volume increases and pressure drops, which makes the moisture content (and other volatile substances) in the melt rapidly vaporized. And the vaporized water is surrounded by the melt film and appears foamy. Under the rotation of the screw, the melt film is crushed, water is separated and discharged directly from the exhaust port (atmospheric exhaust) or from the vacuum auxiliary system (negative exhaust). Subsequently, the molten material, which has removed moisture, flows through the second compression section and the second metering section and passes through the flow path under pressure into the cylinder. When the material in the cylinder reaches a certain amount, the screw stops turning. The piston in the cylinder starts to move, while the check valve set in the flow channel closes, pushing the material into the cavity of the mold for production.

The main difference between this form of exhaust syringe and ordinary exhaust syringe is that the exhaust screw does not have axial displacement during rotation, but



1 - flange; 2 - feed inlet; 3 - barrel; 4 - exhaust screw; 5 - exhaust chamber; 6 - screw head; 7 - connecting sleeve; 8 - flow channel; 9 - nozzle; 10 - storage room; 11 - piston

Fig. 4.10 Structure of exhaust injection molding machine

converts the axial motion of the screw into the axial reciprocity of the piston movement, by which it can establish a greater pressure without damaging the properties of the material. During the entire injection molding, the entire cycle is reduced from the time of traditional injection molding, and the efficiency of its work is improved, which is particularly suitable for rapid formation. In addition, due to the addition of the storage cylinder, a large product can be made.

③ High-speed and super-high-speed injection molding machine [5, 6]

High-speed and super-high-speed injection machine, as the name implies, is a type of injection machine with high injection speed. Generally speaking, the injection machine with injection speed between 300 and 600 m/s is called high-speed injection machine, and the injection machine with injection speed above 600 m/s is called super-high-speed injection machine. The features of them are as follows:

- a. High injection speed, up to 1000 mm/s. Because of the fast injection speed, the molten material is heated by shearing instantaneously when it passes through the runner and gate of the mold, which improves the temperature of the material, decreases the viscosity and has good flow performance. The molded product will not collapse and deform, and has high dimensional accuracy and good reproduction performance. Its product quality accuracy can reach 0.18 mm.
- b. The injection pressure is significantly increased so that fine molded parts can be formed without deformation.
- c. The nozzle is provided with two precision temperature control units. The main purpose of temperature control is to prevent the nozzle temperature of injection molding machine from dropping when molding small thin-walled products, which will affect the quality of molded products.
- d. The machine uses special studs for check rings.

At present, high-speed and super-high-speed injection molding machines mainly include two types: fully electric and hydraulic. Power of all-electric injection machine comes from servo motor, and the original hydraulic cylinder is no longer used. The structure of the whole injection machine is not much different from that of hydraulic type. The main difference is that the former hydraulic motor, square valve, oil circuit board and cylinder are replaced by AC servo motor, ball screw, gear and other parts, and all the electrical components are used to drive the injection machine.

4.3 How 3D Copiers Work

Plastics changes of during injection molding mainly include two basic contents: one is the formation, pressurization and flow of plastic melts; The second is the forming of products. It can be seen from the working sequence diagram (Fig. 4.11). The former occurs in the barrel and the latter occurs in the mold cavity.

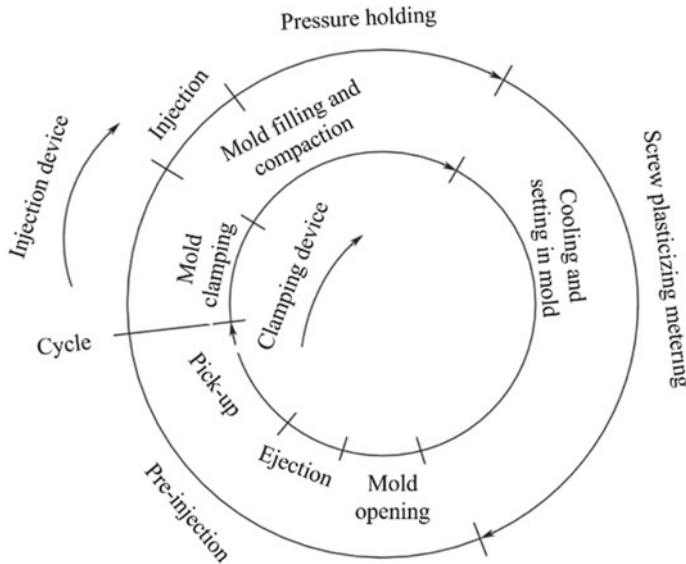


Fig. 4.11 Working sequence of injection molding machine

4.3.1 Plasticization

Plastic is continuously moved forward along the groove under the conveyance of the rotating screw. During plastic movement, it is softened gradually by combined action of external heating and screw shear heat, and finally becomes a molten viscous flow state. The melt in the head of the screw must be pushed back to the screw because of certain pressure, but whether the screw can return and the speed of return obviously depends on the amount of various additional resistance when the screw is returned, such as various friction resistance and the return-relief resistance (cylinder back pressure) of the working oil injected into the cylinder. When the screw returns to a certain position, the pre-plastic metering is finished, the screw stops rotating and is ready for the next injection. Subsequently, when the mold is closed again, the screw moves axially with the help of the cylinder thrust to inject the measured stored melt at the front end. Therefore, the injection machine screw operates continuously under periodic operating conditions, and its plasticizing process mainly consists of two parts.

The first stage is a brief extrusion process. The distance (the corresponding rotating time of the screw) to be retracted as the screw rotates is determined by the amount of injection required. For this reason, it can be considered that the screw rotates in a retractable barrel, and the retraction of the screw during plasticization is converted to the elongation of the storage chamber at the front of the barrel. In this way, the melting mechanism when the injection screw rotates is similar to the usual extrusion process.

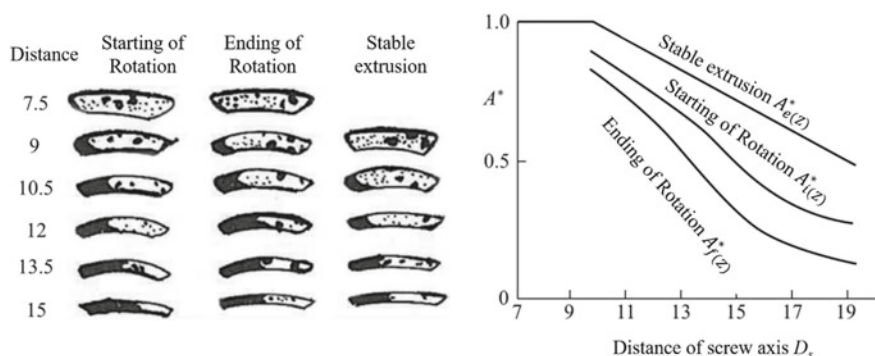


Fig. 4.12 Melting characteristics of injection screw

In the second stage the screw is stationary. At this time, the solid bed continues to melt mainly by the heat transferred from the barrel. When the screw rotates again, the thicker melting film will gradually scrape into the melting pool and the interface between the solid bed and the melting mold will return to the original distribution.

During the periodic rotation of the screw mentioned above, the axial movement of the screw occurs simultaneously. Therefore, the basic factors that determine the melting properties of injection screw are the periodic alternation of rotation and stationary of screw and the axial movement of screw. The former determines the distribution of the melting state of plastics in the groove, while the latter significantly disturbs the melting process of plastics.

(1) Melting physical model

By sampling and analyzing the plastic melt state in the screw groove of the extrusion and injection screw, it is proved that the injection screw has instantaneous melt characteristics (Fig. 4.12).

The melting model in the extruder screw describes the melting process of the material in a stable extrusion state. Under certain operating conditions, when the rotating time of the screw is long enough, the physical process of plastic is changing from solid phase to molten state. In a stable extrusion state, the extrusion volume of the extruder, as well as the melting temperature and pressure of the screw head material, will remain constant. For any given groove cross section, the unmelted solid area A^* (or width X) and the melt film thickness δ , must maintain a fixed value. However, the injection screw is a batch work, and it is necessary to make a certain period of stay in addition to rotation plasticization. During this period, the plastic continues to melt under the thermal conductivity of the barrel, thickening the original melt film, and the solid bed area is reduced to $A_{i(z)}^*$. When the screw is rotated again, the melt film δ will gradually thin, and the solid bed area is correspondingly increased. If the rotation time is long enough, the melt film will return to the thickness of the original stable extrusion. However, the plasticizing working time of injection screw is generally short. For a screw groove section, the melting process of plastic is also in the process of changing the solid bed area from $A_{i(z)}^*$ to $A_{f(z)}^*$ (Fig. 4.13), and

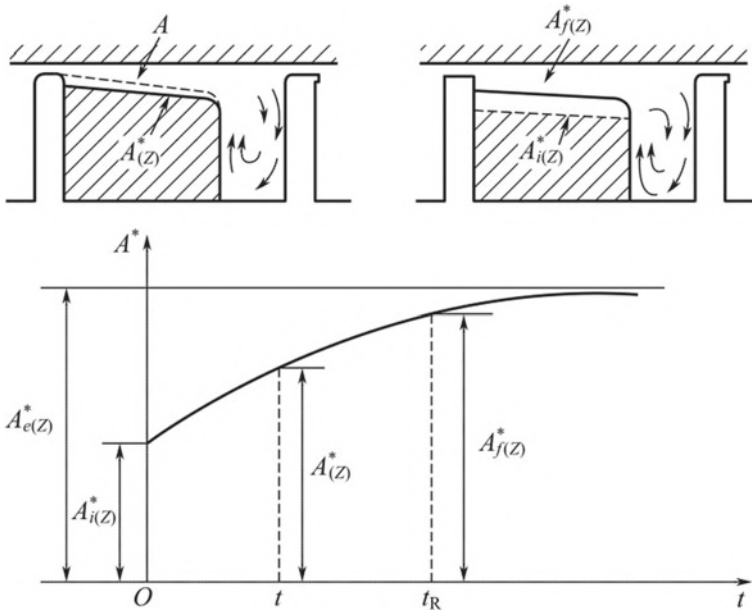


Fig. 4.13 Change of unmelted solid area in injection groove

its area is generally smaller than that of screw in stable extrusion state. During an injection cycle, the melt distribution on the screw is only temporary and a function of time. For the solid bed area of the slot at Z at time t , the following equation can be used:

$$A_{(Z,t)}^* = A_{e(Z)}^* - [A_{f(Z)}^* - A_{i(Z)}^* / (1 - e)^{-\beta N t}] e^{-\beta N t} \quad (4.1)$$

In the formula,

Z —Distance along groove;

t —Screw rotation time, $0 < t < t_R$;

N —Screw Speed;

$A_{e(Z)}^*$ —Smelting distribution in stable state;

$A_{i(Z)}^*$ —Melt Distribution at the Beginning of Screw Rotation;

$A_{f(Z)}^*$ —Melt distribution when screw stops rotating;

β —The melting rate of a material at equilibrium, a parameter related to its rheological and thermophysical properties, is determined experimentally.

$A_{f(Z)}^* - A_{i(Z)}^*$ in the above equation is the part of the melt film thickness, the heat required is transferred from the heating barrel to the interface between the solid bed and the melt film through the gradually thicker melt film. It belongs to the heat conduction problems under moving boundary and phase transition conditions.

The melting hysteresis caused by the axial movement of the screw is not considered in the above analysis. When the machine is working, it is cooled at the feeding port of the barrel. The plastics entering the heating section do not melt immediately, but lag for a period of time (or distance) until a melting film is formed. And the melting mechanism does not begin. The phenomenon that the material begins to heat and melt is not simultaneous is the melting lag. Lag length is usually determined by empirical comparison or experiment.

Figure 4.14 shows the displacement of the screw shaft. For instance, take L_1 as the heating point when the screw is in the retrograde position, L_1^* is the coordinate position point of the corresponding material. L_2^* is the position point where the screw moves forward (injection) to reach the heating position L_1 , and L_2^* is the corresponding material position point of L_2 . When the screw is injected to the front end (i.e. from L_2 to the original L_1) and then rotated and plasticized, the relationship between the locations is as follows:

The distance of screw retraction:

$$S = V_r T_d \quad (4.2)$$

The distance of Material L_2^* relative to the screw L_2 , i.e. hysteresis length:

$$W_d = V_P T_d \quad (4.3)$$

The distance of Material L_2^* relative to the original heating position L_1 :

$$W_1 = (V_P - V_r) T_d \quad (4.4)$$

where,

T_d —the distance of screw rotation;

V_r —the axial speed of screw rotation;

V_P —moving velocity of axial solid bed.

It can be seen that the melting hysteresis will change throughout the plasticizing cycle, making the melting process more complex.

During stable extrusion, the material in the screw groove is only affected by tangential velocity ($v_b = \pi D_s N$). In addition, the injection screw is affected by the axial velocity v_r of the retraction of the plasticizing edge and the injection velocity v_i of the injection, which affects the melting model.

As can be seen from Fig. 4.15, the additional velocity VR will change the velocity distribution in the melt when the screw rotates.

$$v_{bx} = v_b \sin \theta - v_r \cos \theta \quad (4.5)$$

$$v_z = v_b \cos \theta - v_r \sin \theta \quad (4.6)$$

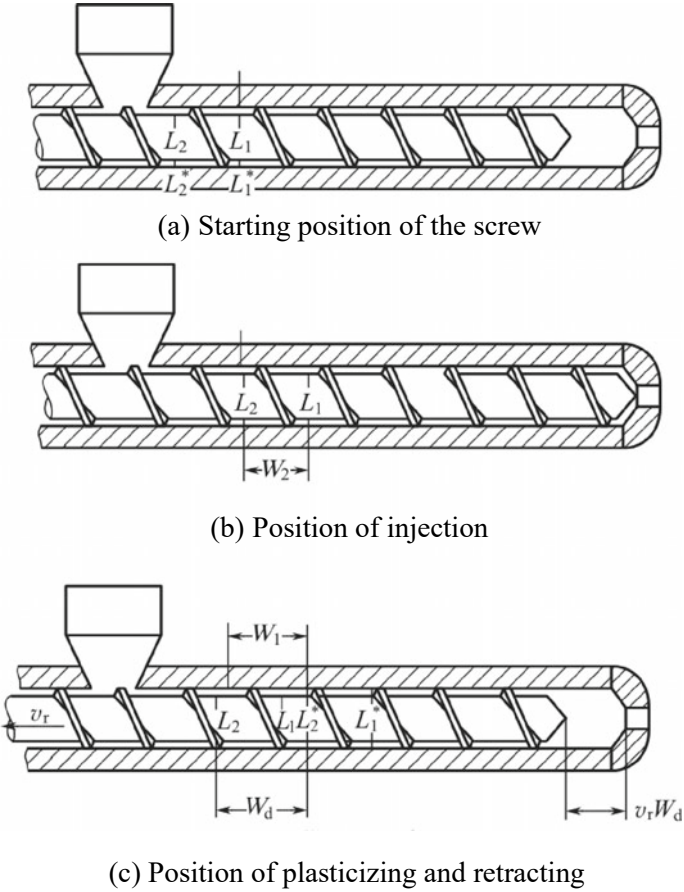
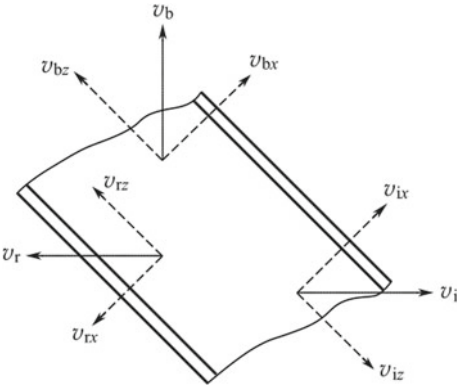


Fig. 4.14 Moving position of screw axial

Fig. 4.15 Additional flow due to axial movement of injection screw



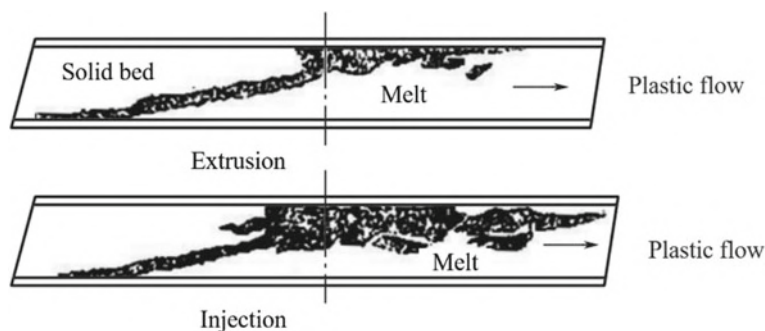


Fig. 4.16 The position of the solid bed in the groove has changed

Therefore, the viscous dissipation (shear heat) is affected and the melting rate is reduced.

Due to the injection speed, considerable cross-flow and reverse-phase flow will occur, and the pressure on the conveyed material will gradually disappear when the screw stops rotating and the pressure field changes periodically throughout the plasticizing cycle.

Therefore, it is possible that gases in the compacted solid bed will burst out. Under the action of cross flow during injection, the solid bed will be dragged from the back of the rib to the thrust surface of the thread. Therefore, it will change the position of the solid bed in the groove and promote the earlier disintegration of the solid bed (see Fig. 4.16), thus reducing the melting efficiency.

In recent years, some scholars not only made various assumptions on the unstable melting model of injection screw, but also made mathematical analysis on the basis of experiments to guide the screw design. Since injection plasticization is a rather complex process, these theories will be tested and developed experimentally.

(2) Main factors affecting the quality of plasticization and their adjustment

The melting process of injection screw is unstable, which is mainly manifested by unstable melting efficiency and large axial temperature difference of the plasticized melt (Figs. 4.17 and 4.18), especially the latter is directly related to the quality of the part.

The melting mechanism and experimental analysis show that the main factors influencing the axial temperature difference of the melt are as follows.

- ① Resin properties: For resins with high viscosity and poor thermophysical properties, the temperature difference is large.
- ② Processing conditions: high screw speed, large stroke, low back pressure of cylinder, large temperature difference of the whole length of cylinder, and large temperature difference.
- ③ Screw length and elements: for ordinary screws with small length diameter ratio and small compression ratio, the temperature difference is large.

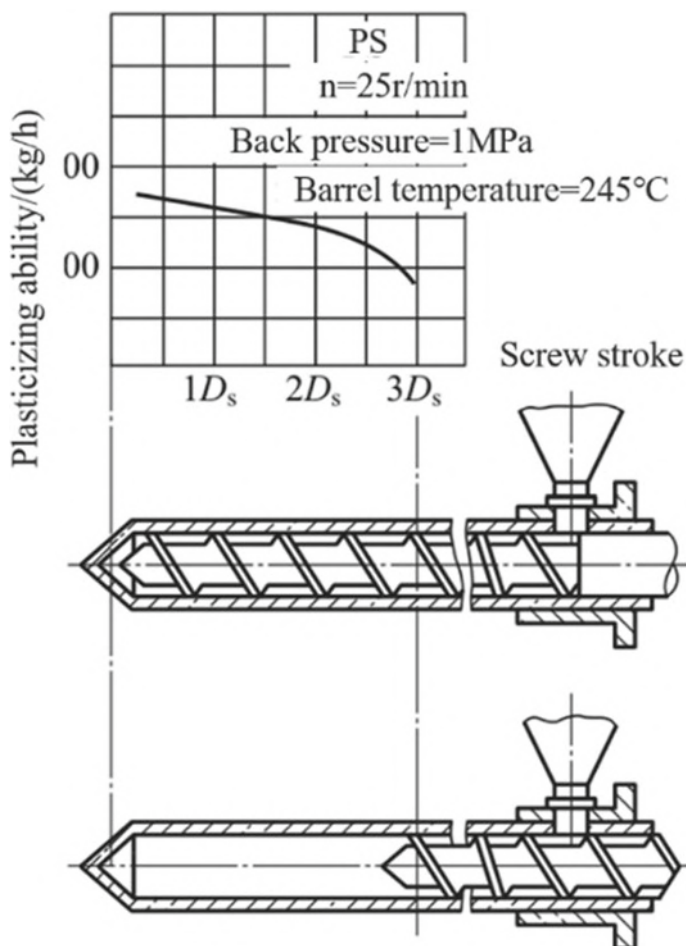


Fig. 4.17 Relationship between plasticizing capacity and stroke of screw

Therefore, in order to ensure the plasticizing quality (reduce the axial temperature difference), for the ordinary injection screw, the rotation speed is generally not more than 30r/min, and the stroke is not more than $3.5 D_s$ (screw diameter).

When the screw is rotating, if the back pressure of the working oil (commonly known as the screw back pressure) is changed, that is, the head pressure of the screw during plasticization is changed. Therefore, the plastic flow condition in the screw groove will be changed, so that the plasticization of the plastic can be adjusted accordingly. The influence of screw back pressure on screw plasticizing ability and plasticizing temperature is shown in Fig. 4.19. Increasing screw back pressure can improve melt homogenization degree and reduce temperature difference. However, when melt temperature is increased, screw conveying ability will decrease. In the

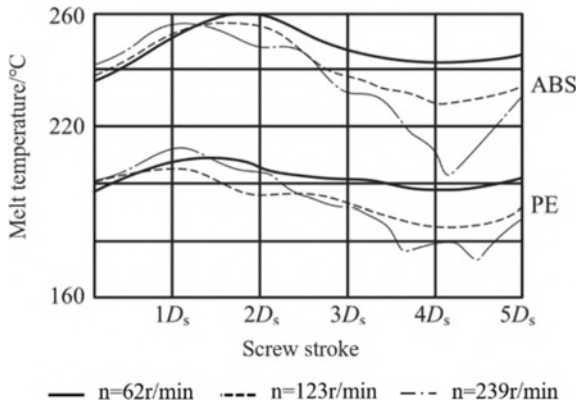


Fig. 4.18 Axial temperature distribution of melt

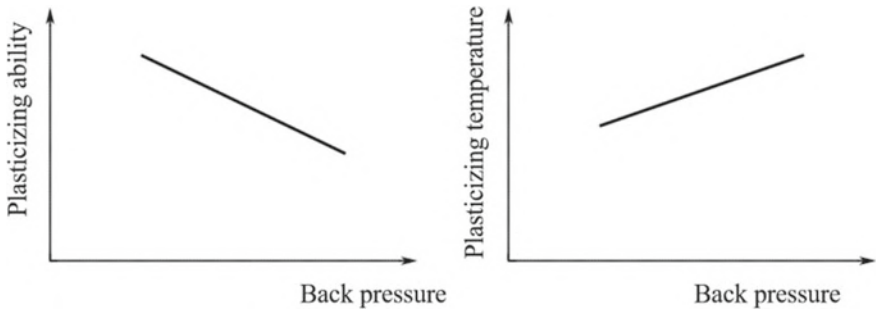


Fig. 4.19 Relationship between screw back pressure and plasticizing ability and plasticizing temperature

case of not affecting the molding cycle, the screw speed should be as low as possible to ensure the plasticizing quality.

Therefore, the most effective way to solve the problem is to design a new type of injection screw and effectively control and adjust the process parameters (screw speed and back pressure).

4.3.2 Mold Filling and Forming

Filling and forming of melts are all the behaviors that occur in the mold. The flow of polymer melts is accompanied by heat exchange, crystallization and orientation processes, as well as the change of flow path cross-section and the non-uniformity of temperature field of mold, so the process is very complex. However, this process

is closely related to the quality of products. Almost at the same time that injection molding technology has been paid attention to and developed, observation and Research on injection molding process has begun.

The plastic state in the mold can be expressed by the Spence - Gilmore equation of state:

$$(p + \pi)(V - W) = RT \quad (4.7)$$

Where

P—plastic (melt) pressure.

V—specific volume of plastics;

T—plastic temperature;

R, π , W—constants depending on the properties of the plastic.

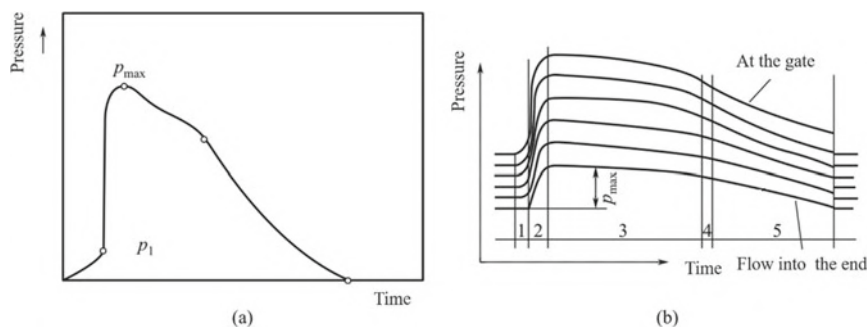
It can be seen that the quality of the product depends mainly on the specific volume change of the plastic when it is molded. The pressure, temperature and specific volume of the molding process at high temperature and pressure will undoubtedly be regarded as the basic variables of the thermodynamic process. The state (specific volume) of the plastic will depend on the pressure and temperature. Equation (4.7) shows that when temperature T is constant, i.e. isothermal process, the melt pressure P and specific volume V in the cavity are directly related, which is very close to the filling stage in the forming cycle. After the gate is sealed in the cooling stage, V-W is constant, and temperature T will directly affect pressure P.

Besides the static effect on the plastic melt, the pressure is also related to the flow properties of the melt during filling. The filling pressure and flow law required by melt during filling can be analyzed by referring to relevant knowledge in rheology.

Therefore, the change of in-mold plastic pressure (cavity pressure) directly reflects the in-mold forming process and can be used as an important means to effectively control the quality of products.

(1) Cavity pressure

Cavity pressure varies in a molding cycle as shown in Fig. 4.20. Cavity pressure increases linearly to p with the increase of flow length during filling. When the melt fills the cavity, the pressure in the cavity rapidly increases to the maximum p , and there is a significant turning point in the pressure. Then the machine maintains the pressure. As the cylinder pressure enters the low pressure, the pressure of the melt in the cavity decreases due to the cooling of the mold. After pressure retaining is terminated and cylinder pressure is removed, the cavity pressure will continue to drop at a faster rate, and the final cavity pressure will determine the residual stress of the product.



1 - mold filling; 2 - compaction; 3 - pressure holding; 4 - pressure relief and backflow; 5 - product cooling

Fig. 4.20 Cavity pressure change

The pressure change can be divided into the following four stages depending on the molding process.

① Stage of filling and compaction

The time from the screw moving forward to the cavity filled with molten material is the filling period. During this period, the pressure increases with the increase of melt flow distance, and the injection rate is stable and reaches the maximum value. At this time, the flow state of the melt in the mold cavity has a direct impact on the surface quality, molecular orientation and internal stress of the product. Therefore, the injection speed and pressure, according to the characteristics of plastic products and mold structure, choose different program design, to achieve a more ideal filling process.

When the molten material fills the mold cavity, the pressure rises rapidly to the maximum value (the value depends on the injection pressure), and the injection speed decreases rapidly to compact the molten material in the mold cavity.

② Stage of pressure holding and tightening

When the mold cavity is filled with melt, the specific volume of the melt changes due to the cooling effect of the mold, resulting in shrinkage of the product. For this reason, the screw must still act on the melt with certain pressure for shrinkage and expansion. The duration of holding pressure and the magnitude of holding pressure are directly related to the stress of the product until the screw is relieved. High pressure makes the product shrink slightly. However, when the pressure is too high, it is easy to generate high stress and make it difficult to demold.

③ Stage of backflow

When the holding pressure is removed, the cavity pressure is higher than the melt pressure from the gate to the screw. At this time, the plastic in the mold cavity has not been completely cured, and the inner plastic also has a certain fluidity. Thus, it

is possible to make a slight reverse flow to the outside of the gate (i.e. outside the mold cavity), and the pressure of the mold cavity will also decrease. Obviously, the occurrence of backflow and the extent of it are mainly determined by the closure condition of the gate. The backward flow of the melt makes the product prone to defects such as shrinkage and hollow. If the gate is essentially closed and continues to be filled (back filled) under high pressure, there will be residual stress around the gate. In order to avoid the above phenomena, it is better to set the holding pressure according to the reduction of the cavity pressure to achieve programmed control. Precise control of the cavity pressure and plastic temperature when the gate is closed plays an important role in obtaining high-precision plastic products.

④ Stage of product cooling

This stage starts from the time when the gate plastic is completely frozen to the time when the product is taken out after the mold is opened. The plastic in mold continues to cool at this stage so that the product has sufficient stiffness during demolding. When opening the mold, there is a certain pressure on the plastic in the mold, which is called residual pressure. It is related to the holding time and the holding pressure.

(2) Pressure distribution and pressure loss in the whole process

In the pressure image, the highest pressure P_{DC} is the basic condition of filling flow, which is called dynamic pressure. P_{SC} is the highest pressure in compaction stage, which is called static pressure. If the pressure is measured in the whole process, and the dynamic and static pressure at the corresponding position can be expressed as the whole process distribution as shown in Fig. 4.21. It can be known that there is not only dynamic pressure loss but also static pressure loss for polymer melt. This phenomenon is determined by the characteristic that the effect of polymer melt on pressure transfer is a function of time.

4.4 Basic Parameters of 3D Copiers

4.4.1 Main Parameters of the Injection Unit [7]

The basic parameters and meanings of the injection system are as follows.

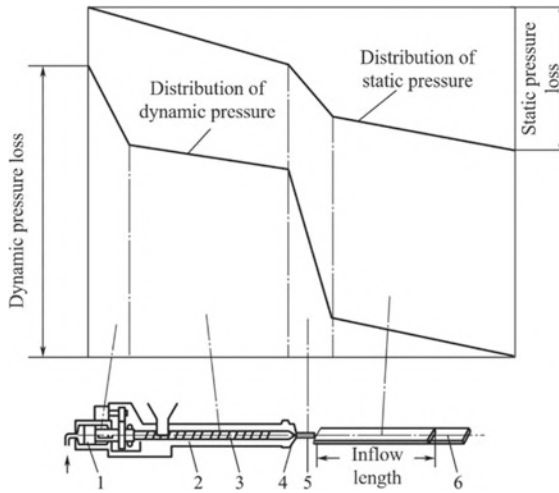
Screw diameter d_s : outer diameter of injection screw, unit: mm;

Length diameter ratio of screw L/d_s : the ratio of the effective length of the screw thread to its outer diameter;

Theoretical Injection Volume V_i : the maximum theoretical volume that can be injected in one injection process, unit: cm^3 ;

Injection quantity W_i : the maximum theoretical mass that can be injected in one injection process, unit: g;

Injection pressure p_i : the maximum pressure on the molten material at the head of screw during injection, unit: MPa;



1 - injection cylinder; 2 - barrel; 3 - screw; 4 - nozzle; 5 - flow channel; 6 - product

Fig. 4.21 Pressure loss during injection

Injection rate q_i : the maximum theoretical volume that can be injected in unit time, unit: cm^3/s ;

Injection power N_i : the maximum power of screw pushing molten material, unit: kW;

Plasticizing capacity Q_s : the mass of the material that can be plasticized by the injection system in unit time, unit: g/s;

Screw speed n_s : the maximum number of revolutions per minute of screw during pre-plasticization, unit: r/min;

Injection seat thrust P_n : the pressure when the injection nozzle is close to the mold, unit: N;

Barrel heating power T_b : the total heat energy supplied by the barrel heating element to the barrel surface per unit time, unit: kW.

The main parameters and calculation of the injection system are as follows.

(1) Theoretical Injection Volume V_i

The theoretical maximum volume that the screw (or plunger) can discharge during injection is called the theoretical injection volume of the machine. Theoretical injection volume is an important index to measure the scale of an injection machine. According to its definition, if the maximum injection stroke (S_{imax}) of the screw is known, it can be calculated by the following formula:

$$V_i = \frac{\pi}{4} d_s^2 S_{imax} \quad (4.8)$$

where

d_s —screw diameter, mm;

S_{imax} —maximum injection stroke, mm.

(2) Injection volume

The maximum mass of resin that can be injected from the nozzle under the no-mold (air injection) operation of the machine is called the injection quality of the machine.

By definition, the injection volume should be equal to the theoretical injection volume multiplied by the melt density. However, considering the density variation of melt and reflux during injection, density correction factor α_1 and reflux correction factor α_2 are often introduced, which are collectively referred to as injection correction factor α . The formula for calculating the injection volume is as follows:

$$W_i = \alpha \rho V_1 = \alpha_1 \alpha_2 \rho V_i \quad (4.9)$$

where,

V_1 —Theoretical injection volume, cm^3 .

Injection machine specifications are mostly indicated by the injection volume of polystyrene (PS).

(3) Injection pressure p_i

The injection pressure is defined as the maximum pressure on the molten material at the head of the screw in the injection process. It is also the maximum pressure of the screw to the molten material. Therefore, it can be calculated by the pressure P_0 of the working oil in the injection cylinder.

$$p_i = \frac{A_0}{A_s} P_0 \quad (4.10)$$

where

A_0 —effective sectional area of injection cylinder;

A_s —cross sectional area of barrel inner hole.

(4) Injection rate q_i

The injection rate represents the amount of melt ejected from the nozzle per unit time. Its theoretical value is the product of cylinder section and velocity. According to the definition, q_i is calculated as follows.

$$q_i = \frac{V_i}{t_i} = \frac{\pi d_s^2 S_{imax}}{t_i} \quad (4.11)$$

where

d_s —screw diameter, mm.

S_{imax} —maximum injection stroke, mm;

t_i —injection time, s.

(5) Plasticizing capacity Q_s

Plasticizing capacity of injection system refers to the mass of plasticized material in unit time, which is equal to the melt conveying capacity of homogenizing section of screw.

$$Q_s = \beta d_s^3 n_s \quad (4.12)$$

where

β —The plasticization coefficient, related to the material;

d_s —screw diameter, mm;

n_s —screw speed, r/min.

4.4.2 Main Parameters of the Clamping Unit [8]

The main parameters of the clamping system are as follows.

Clamping force P_{cm} : the pressure between the molds after clamping, unit: kN;

Jacking force P_J : the maximum thrust required by the ejection device to eject the product, unit: kN;

Opening and closing speed V_m : the maximum stroke per unit time in the process of opening and closing the mold;

Moving stroke S_m : the maximum distance of movable template;

Ejection stroke S_j : the maximum distance that the ejection device can eject the product.

(1) Clamping force P_{cm}

Usually, part of the melt pressure is lost in the process of injection, but part of the melt pressure is retained, which is called cavity pressure or expanding force. In order to prevent the mold from being expanded by the expanding force, it is necessary to apply a clamping force to the mold, which is called clamping force. The clamping force, like the injection quantity, is also an important index reflecting the product capability of the injection molding machine, so it is usually indicated in the specifications of the injection molding machine. The formulas for calculating the closing force are as follows.

$$P_{\text{cm}} \geq 0.1 p_{\text{dm}} A \quad (4.13)$$

where

p_{dm} —dynamic pressure of the cavity;

A—Maximum projection area of product on partition surface.

(2) Pushing force P_j

The ejection force refers to the maximum thrust of the ejection device ejecting the product. The empirical calculation formula is as follows.

$$P_j = C_j P_{cm} \quad (4.14)$$

C_j refers to the empirical coefficient, which is 0.02~0.03. It is small when clamping force is high.

4.5 Structural Design of 3D Copier

4.5.1 Injection Device

During the working process of injection molding machine, injection device mainly realizes three functions: plasticizing metering, injection, pressure retaining and compensating. It is the core of polymer melting plasticization, and determines the homogeneity of plastic melting and then effects the quality of products. At present, screw injection system is most widely used, which mainly includes hopper, injection screw, barrel, nozzle and other components. The basic requirements for its design are:

- ① A certain amount of melt can be injected and plasticized evenly within a specified time.
- ② Injection rate and injection pressure can be adjusted within injection specification according to product size and structure.

The structural design of injection system mainly includes the design of injection screw, barrel and nozzle.

(1) Structure design of screw

At present, major manufacturers continue to develop new studs to expand the form of studs, such as special studs for PVC. However, these screws were designed based on conventional injection-molded screws. Generally, injection-molded screws consist of mounting section, threaded section and screw head.

① Screw threaded section design

The threaded section of common injection-molded screw is divided into three sections (Fig. 4.22): feeding section, compression section (melting section) and homogenization section (metering section). The main parameters of each section include length,

groove depth, pitch, etc. Differences of these geometric parameters will affect the melt plasticization measurement of polymers and the quality of products

② Design of screw head

Unlike the working process of the extruder, the injection process of the injection machine is intermittent and there is axial movement of the injection screw. Therefore, it is more likely that the melt will leak back when the injection screw is working, especially when molding low-viscosity materials. Thus, in the design of injection-molded screws, a structure to prevent the melt from leaking back must be designed at the head of the screw.

As shown in Fig. 4.23, this screw head is called a flat-tip screw head. It is characterized by a small taper angle or thread on the head of the screw. The gap between the cylinder and the cylinder is very small after installation (Fig. 4.24), which can well prevent the return of high-viscosity materials. Therefore, it is mainly suitable for high viscosity or heat sensitive plastics such as PVC.

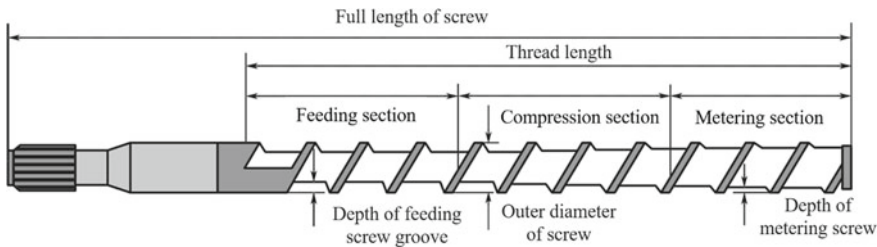


Fig. 4.22 Screw sections

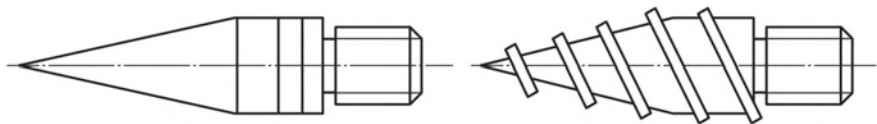


Fig. 4.23 Flat-tip screw head

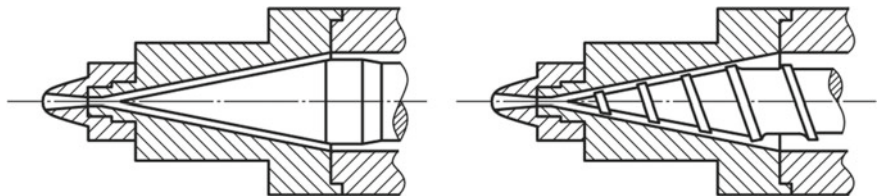
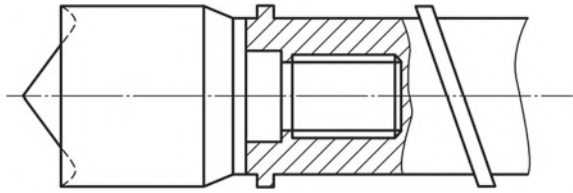


Fig. 4.24 Sectional drawing of flat-tip screw head installed

Fig. 4.25 Blunt-tip screw head



As shown in Fig. 4.25, this screw head is called blunt-tip screw head. Its head is a zigzag surface of “mountain”. It acts like a piston and is mainly used for molding plastics such as PC and PMMA with high transparency.

In addition, the most widely used check screw head is shown in Fig. 4.26. It uses a check ring structure and works similarly to a check valve. During the pre-plasticization, the screw rotates, and the molten material coming out of the screw groove has a certain pressure to push the check ring open. So, it will form the state of the lower side in the figure, and the molten material enters the storage chamber at the front end of the screw. During injection, the screw moves forward until the conical surface of the screw contacts the right end of the check ring. Thus, it will form the upper structure in the figure, so as to prevent the leakage of molten material. It is mostly used in the processing of low viscosity plastics.

There are also various forms of check ring, such as annular screw head (Fig. 4.27). The check ring rotates relative to the screw, which is suitable for medium and low viscosity plastics.

Claw shaped screw head (Fig. 4.28) limits the rotation of the check ring through the groove structure, and it avoids the overheating of the molten material shearing

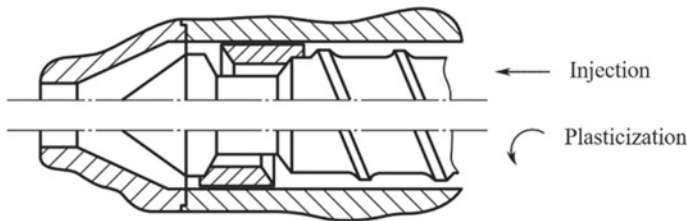


Fig. 4.26 Working principle of check ring screw head

Fig. 4.27 Annular screw head

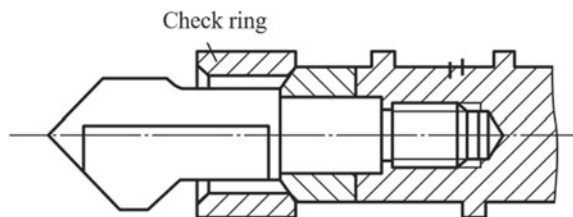
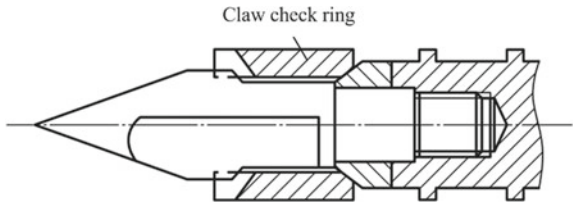


Fig. 4.28 Claw shaped screw head



between the screw and the check ring. It is suitable for medium and low viscosity plastics.

Rolling ball type check ring is shown in Fig. 4.29. Rolling ball is used between the check ring and the screw, so that there is rolling friction between the check ring and the screw. This structure has the characteristics of fast pressure rise, accurate injection volume, and long service life. Therefore, it is suitable for medium and low viscosity plastics.

Pin type screw head is shown in Fig. 4.30, screw head with mixing pin, played a further homogenization role, suitable for low viscosity plastics.

Split flow screw head is shown in Fig. 4.31. The screw head is provided with an inclined slot to further homogenize. It is suitable for medium and low viscosity plastics.

Fig. 4.29 Rolling ball screw head

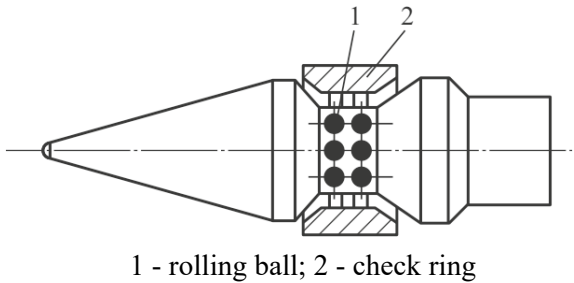


Fig. 4.30 Pin screw head

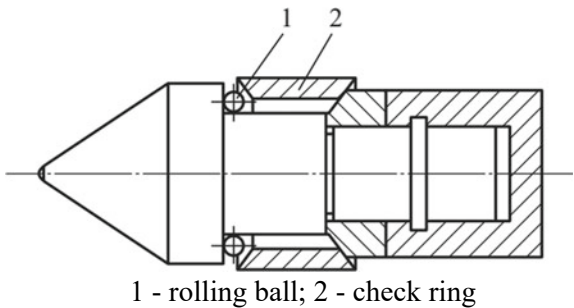
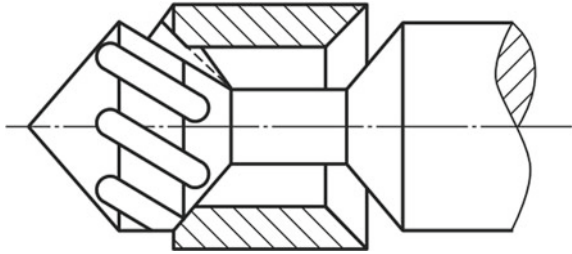


Fig. 4.31 Split screw head

A good check screw head should be opened and closed flexibly, and can prevent the molten material from leaking back to the maximum extent. Therefore, the design requirements are as follows:

- a. The fit clearance between check ring and screw should be appropriate. If the clearance is too large, the leakage will increase, and if the clearance is too small, the flexibility will be affected;
 - b. The head of screw should have enough flow section during pre-plasticization;
 - c. Screw head and screw should be connected by reverse thread.
- ③ New injection screw structure

Screw is the core component of polymer plasticization, and injection screw is the development extension of extrusion screw. Although the above universal screw is widely used, its plasticizing effect can't meet the requirements of precision injection molding. In order to improve the plasticizing quality, some screw structures of extruder are also used in injection molding machine, such as separate screw (Fig. 4.32), barrier screw (Fig. 4.33), etc. Both of them separate the solid and liquid phases by special structure, so that the solid phase can be melted better.

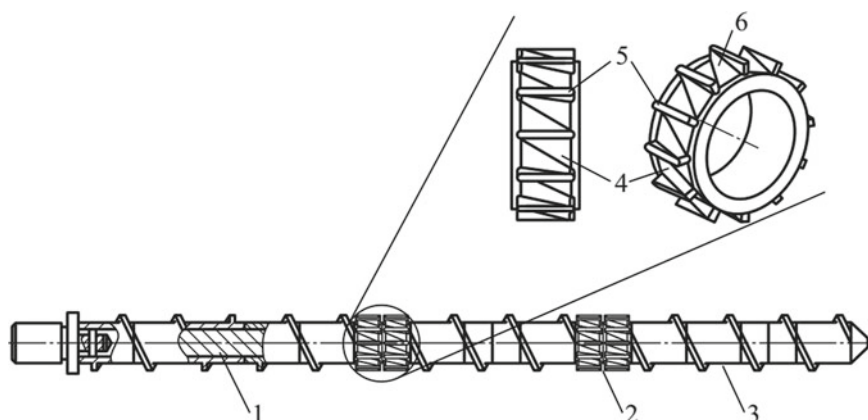
**Fig. 4.32** Structure of separating screw [9]**Fig. 4.33** Structure of barrier screw

In the previous paper, we mentioned a new type of heat transfer enhancement screw field synergy screw. It has been proved that it can effectively improve the synergistic effect of velocity field and heat flow field, enhance mass and heat transfer, improve melt plasticization quality and improve melt temperature uniformity.

Figure 4.34 shows the building block type test screw and the new enhanced heat transfer structure. Figure 4.35 shows the different screw structures printed by FDM 3D printer and the assembled screw.

(2) Design of barrel structure

The barrel is another important part of the injection system. It is connected with the hopper and injection seat, with screw inside and heating element outside, as shown in Figs. 4.36, 4.37 and 4.38. The barrel mainly includes three structural forms.



1 - screw mandrel; 2 - a new type of enhanced heat transfer structure; 3 - ordinary screw structure; 4 - dividing slot; 5 - dividing edge; 6 - 90 ° torsion surface

Fig. 4.34 Building block test screw and new enhanced heat transfer structure



Fig. 4.35 3D printing screw elements with different configurations (left) and assembled building block screw (right)

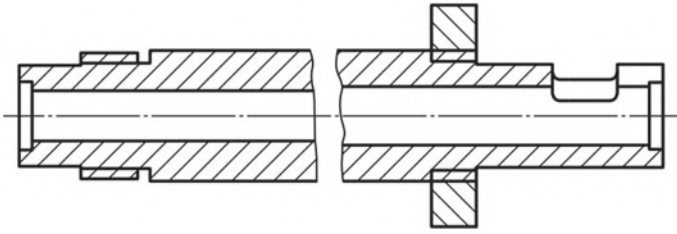


Fig. 4.36 Integral barrel

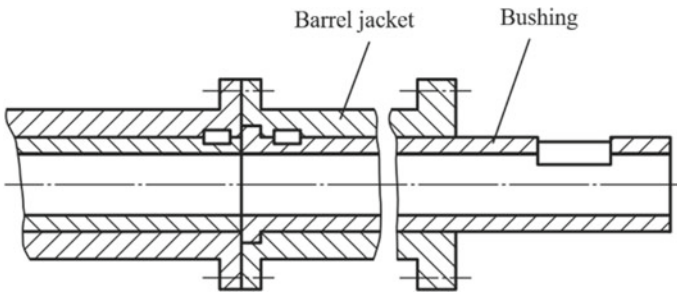


Fig. 4.37 Matching barrel of liner set

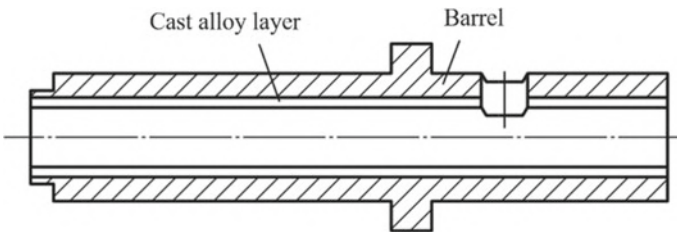


Fig. 4.38 Lining casting barrel

① Integral type

Its characteristic is that the barrel is heated evenly, and the accuracy is easy to be guaranteed, especially the assembly accuracy. The disadvantage is that the inner surface is difficult to clean and repair (Fig. 4.36).

② Matching of lining set type

It is easy to clean and repair after segmenting the barrel. The coat can be made of cheaper carbon steel, which saves the cost. However, the assembly of the two-stage

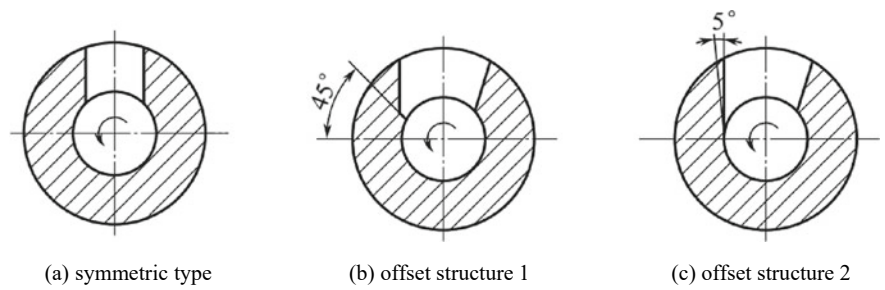


Fig. 4.39 Structure of feeding port

type is more difficult, and the accuracy is not as high as that of the integral type (Fig. 4.37).

③ Lining casting type

Its characteristics are that the cast alloy layer is firmly combined with the outer barrel, high wear resistance, long service life and cost saving (Fig. 4.38).

Its structural design mainly includes the following aspects.

① Feeding port

At present, the injection system of 3D copier mostly uses self-weight feeding. Therefore, the design of barrel feeding port should enhance the conveying capacity of plastics as much as possible. At present, there are two widely used feeding port types: symmetrical type and offset type, as shown in Fig. 4.39.

From the conveying effect, the offset type is slightly better than the symmetrical type.

② Clearance between barrel and screw

In order to prevent material from leaking back and affect the plasticizing quality, the clearance between the barrel and screw is generally very small. However, in order to facilitate assembly and reduce the power consumption of screw, the clearance can't be too small. According to the experience, generally, $0.002d_s \sim 0.005d_s$ can be used. Refer to the experience data in Table 4.3 for design.

In addition to meeting the above range, the clearance values of the three sections of the screw are also different. The gap value of homogenizing section of screw is stricter, so the gap is smaller. The design of clearance value should meet the following conditions as far as possible:

Table 4.3 Clearance between barrel and screw/mm

Screw diameter	$\geq 15 \sim 25$	$> 25 \sim 50$	$> 50 \sim 80$	$> 80 \sim 110$	$> 110 \sim 150$	$> 150 \sim 200$	$> 200 \sim 240$	> 240
Maximum radial clearance	≤ 0.12	≤ 0.20	≤ 0.30	≤ 0.35	≤ 0.45	≤ 0.50	≤ 0.60	≤ 0.70

$$\delta_1 < \delta_2 < \delta_3 \quad (4.15)$$

Among them, δ_1 , δ_2 , δ_3 represents the clearance between homogenizing section, melting section, feeding section and barrel respectively.

③ Inner diameter, outer diameter and wall thickness of barrel

As mentioned earlier, the barrel needs internal screw and external heating element. Therefore, the wall thickness of the barrel can neither be too thick nor too thin. Too thick is not only cumbersome, but also affects the heat transfer; Too thin is easy to cause strength problems, and it is difficult to obtain stable temperature conditions due to small heat capacity. Considering the problems of heat capacity and thermal inertia, the inner and outer diameters of the barrel are generally selected according to the following formula:

$$\frac{D_0}{D_b} = K \quad (4.16)$$

where, D_0 is the outer diameter of barrel; D_b is the inner diameter of barrel; K is the empirical coefficient (generally 2~2.5).

Considering the strength, K also needs to satisfy the following equation:

$$1 - \frac{1}{K} \geq \frac{1}{2} \left(\sqrt{\frac{[\sigma]}{[\sigma] - \sqrt{3} p_i}} - 1 \right) \quad (4.17)$$

where, D_0 is the outer diameter of barrel; $[\sigma]$ Refers to the allowable stress of the material; p_i is the injection pressure.

Considering the above two points, a suitable K value can be obtained.

As we know, the clearance between screw and barrel is very small, which is $0.002d_s \sim 0.005d_s$. Therefore, the screw diameter d_s can be used as the inner diameter D_b of the barrel for calculation, and then D_0 can be calculated from $D_0 = K D_b$. Finally, the barrel wall thickness δ can be obtained.

④ Connecting structure form of barrel and front material barrel

The barrel is not directly connected to the nozzle, but through a transition part such as the feeder barrel. As shown in Fig. 4.40, the connection between the barrel and the feeder barrel needs to be strictly sealed. There are three common connection types. Threaded connections are easy to assemble and disassemble, but long-term use will loosen the thread deformation and cause spills, so this structure is mostly used in small injection molding machines. Flanged connections are used in small and medium-sized injection molding machines because of their better sealing and longer service life. Large injection molding machines mostly use flange threaded composite connection, which combines the advantages of the above two structures.

⑤ Innovative design of barrel

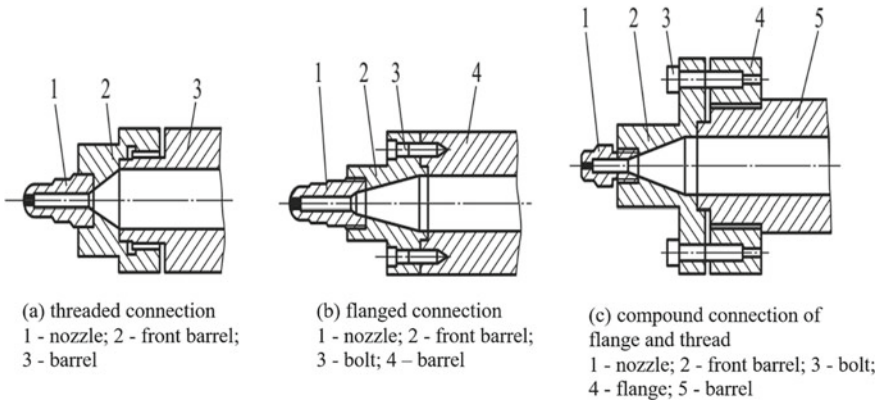


Fig. 4.40 Connection form of barrel and front feeding barrel

From the point of view of structural innovation, Ch. Hopmann of Aachen University of Technology, Germany, has developed a new injection plasticizing system. As shown in Fig. 4.41, he designs the groove on the cylinder. The screw is in the form of a piston and advanced while rotating. Their research shows that such a structure has a good homogenization effect and can produce a shorter residence time. Repetition precision of injection molding has been greatly improved, and it has a good development prospect in the field of micro-injection molding [10]. Generally speaking, there are not many innovative improvements on barrel structure.

(3) Structure design of nozzle

The nozzle is an important component that connects the injection system with the mold system. As the nozzle gradually decreases from the inlet to the outlet, under the pressure of the screw, the shear speed and pressure of the melt flow through the nozzle are significantly increased. And some pressure losses will further increase the melt temperature and improve the homogenization effect. When holding pressure, the nozzle also needs to be filled and compensated, plus the nozzle needs to be closely

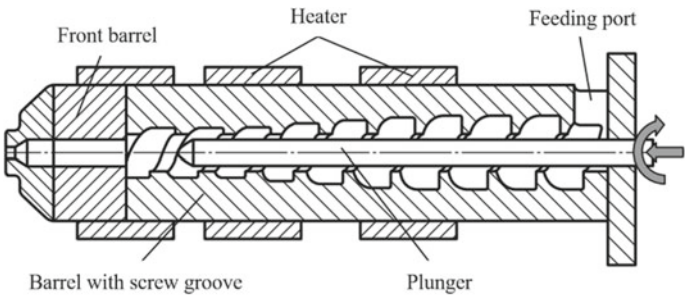


Fig. 4.41 New IKV injection molding system

fitted to the main runner sleeve of the mold. These all make the nozzle design very important and require very high accuracy. This is why the nozzles are often designed separately from the barrel.

Common nozzle configurations are open nozzles, locking nozzles and special purpose nozzles.

The flow path of an open nozzle is always open as shown in Fig. 4.42. The pressure loss is small and the effect of supplementation is good, but it is easy to form cold material and “salivation”. Therefore, it is mainly used to mold thick-walled products and process plastics with poor thermal stability and high viscosity.

Locking nozzles are designed to prevent “Salivation” by means of a flow path locking structure, as shown in Fig. 4.43. Locking can be achieved by means of structures such as springs. Injection is the use of a melt to press the locked pin apart. This structure is complex and is mostly used to process low-viscosity plastics.

Special purpose nozzles are nozzles designed to enhance plasticization and mixing uniformity. The structure design of the nozzle mainly includes the nozzle diameter and the spherical radius of the nozzle head.

① Nozzle bore d_n

Nozzle aperture refers to the orifice at the outlet of the nozzle flow channel (i.e. the smallest orifice from which the molten material flows). So, it is directly related to the pressure of melt injection, shear heating and shrinkage. Its design is calculated

Fig. 4.42 Open nozzle

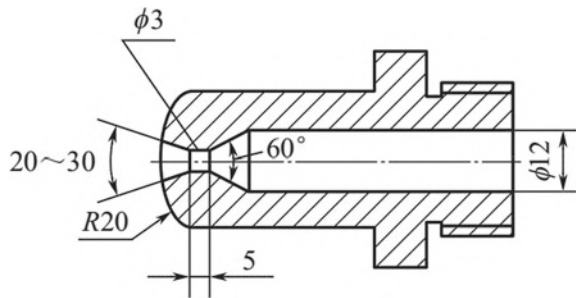
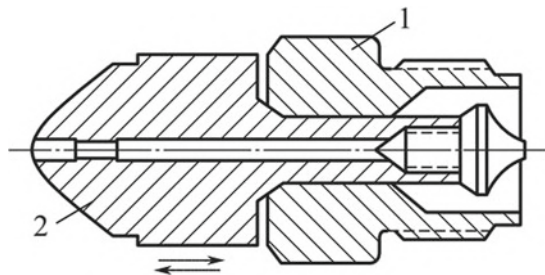


Fig. 4.43 Locking nozzle



1 - nozzle body; 2 - nozzle core

Table 4.4 Determination of nozzle spherical radius/mm

Spherical radius	Effective spacing of tie rods
10	200~559
15	560~799
20	800~1119
35	1120~2240

according to the following formula:

$$d_n = k_m \sqrt[3]{q_i} \quad (4.18)$$

where,

d_n refers to the nozzle diameter, mm; q_i refers to the injection rate, cm^3/s ; k_m refers to the performance index of plastics. Materials with high thermal sensitivity and viscosity are 0.65~0.80 and general plastics are 0.35~0.4.

② Spherical radius of nozzle

The determination of the nozzle spherical radius refers to the national professional standard ZBG 95,003-87 and takes the value according to the effective spacing of the tie rods as shown in Table 4.4.

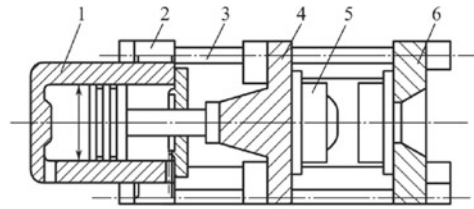
4.5.2 Clamping Device

The mold clamping device is the part that determines the shape of the product and is where the molten material is finally formed. Its main function is to ensure the reliable opening and closing of the mold and the ejection of the product, so its quality has a significant impact on the dimensional accuracy of the product. The closing device mainly consists of mold opening and closing mechanism, pull rod, adjusting mechanism, ejection mechanism, fixing template and safety protection mechanism. The basic requirements of its design are: to provide sufficient clamping force; reliable strength and rigidity; reasonable structure and its design should maximize the energy utilization.

The design of clamping device mainly includes closing mechanism, ejection mechanism, template and tension rod.

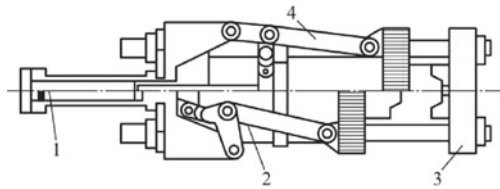
(1) Design of clamping mechanism

Clamping mechanism includes the forms of direct pressing and toggle, direct pressing type structure as shown in Fig. 4.44a, one end of the movable template is mold, the other end is the piston which moves the pistons through the liquid pressure. The design of this mechanism only needs to consider the strength and other factors. The toggle mechanism is shown in Fig. 4.44b, which has the advantage of amplifying the



(a) direct pressing clamping mechanism

1 - clamping cylinder; 2 - back template; 3- pull rod; 4 - movable template; 5- mold; 6 - front template



(b) toggle clamping mechanism

1 - mold moving cylinder; 2 - toggle position with opening mold; 3 - static mold; 4 - toggle position with clamping mold

Fig. 4.44 Forms of clamping mechanism

force. The mold is self-locking after being locked and enables the movable template to achieve slow-fast-slow speed characteristics. With the development of electric structure, the form of the mold clamping mechanism has been expanded.

At present, according to the transmission form, the clamping mechanism of injection molding machines on the market can be divided into four types: full mechanical type (rarely used), mechanical connecting rod type, full hydraulic direct pressure type and hydraulic mechanical type, as shown in Fig. 4.45.

For the design of toggle mechanism, simple mathematical calculation has been unable to solve. With the development of MATLAB, ADMAS and other kinds of software, it is more and more convenient to use computer for optimizing the size and analyzing the dynamics of toggle mechanism.

About the design of clamping mechanism, we need to know several concepts of force.

Clamping force P_{cm} : the clamping force formed between the molds after clamping and before injection of molten material.

Closing force P_z : after the injection of molten material, the clamping force will be partially offset due to the expansion force, and the remaining clamping force between the molds is called clamping force.

Mold moving force P_m : the force that pushes the movable template to move.

Expanding force P_s : the pressure that is formed by molten material in the mold cavity to separate the mold.

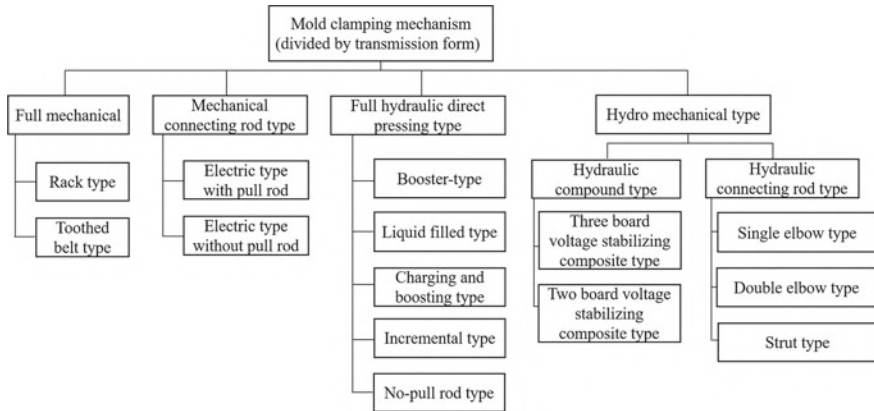


Fig. 4.45 Classification of clamping mechanism of injection molding machine by transmission type [11]

In the design of clamping mechanism, the design of direct pressing structure is relatively simple. The clamping force is proportional to the hydraulic pressure, and the hydraulic pressure directly drives the template to lock the mold. The clamping force formed in the process of clamping is as follows:

$$P_{cm} = \frac{\pi}{4} D_0^2 p_0 \times 10^3 \quad (4.19)$$

where

D_0 —diameter of clamping cylinder, m;
 p_0 —working oil pressure, MPa.

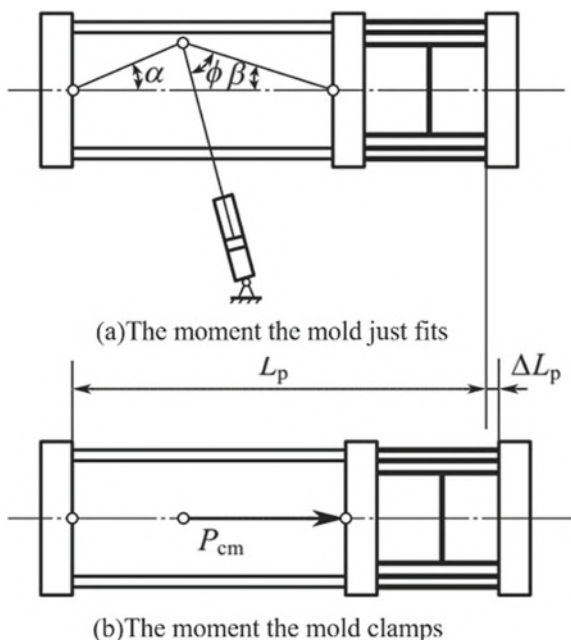
However, compared with the toggle mechanism, the direct press mechanism does not have the function of force amplification, so the toggle mechanism is often used in industry. For the design of toggle clamping mechanism, the drawing method was first used. The method is to simplify the structure of the clamping toggle. First, establish the relationship between the clamping force, clamping force and the structural parameters of the toggle according to the geometric relationship and the relevant knowledge of material mechanics. Then the optimal solution is solved. For example, Fig. 4.46 is the working principle diagram of the single toggle clamping mechanism.

It can be seen from Fig. 4.46 that during the operation of the toggle clamping mechanism, the pull rod has a certain deformation. Its deformation ΔL_p can be expressed by the following formula:

$$\Delta L_p = \frac{P_{cm} L_p}{Z E F_p} \quad (4.20)$$

It can also be rewritten as follows:

Fig. 4.46 Principle of toggle clamping mechanism



$$P_{cm} = Z C_p \Delta L_p \quad (4.21)$$

where

L_p —length of pull rod, m;

F_p —sectional area of tie rod, m²;

ΔL_p —deformation of pull rod, m;

P_{cm} —clamping force, N;

E —elastic modulus of pull rod material, PA;

Z —number of pull rods;

C_p —rigidity of tie rod, $C_p = \frac{E F_p}{L_p}$ $M = \frac{P_m}{P_0} = \frac{\cos \beta \sin \phi}{\sin(\alpha + \beta)}$ N/m.

The greatest feature of the elbow mechanism is its powerful amplification. That is, when the cylinder thrust is P_0 , the displacement force P_m is often much greater than it. We call the ratio of the two magnifications M and the formula is as follows (the meanings of each angle are shown in Fig. 4.46):

$$M = \frac{P_m}{P_0} = \frac{\cos \beta \sin \phi}{\sin(\alpha + \beta)} \quad (4.22)$$

However, even for single-elbow structures, mathematical solutions are cumbersome. Moreover, the magnification of single elbow closing mechanism is about 10 times, and the bearing capacity is limited. Therefore, in industry, hyperbolic elbow closing mechanism or other complex structural forms are often used. For the design of

hyperbolic elbow structure, the mathematical calculation is more impossible. Therefore, various software can be used to assist the design of closing mechanism, such as MATLAB, ADAMS, ANSYS, etc. Current design generally follows the following steps.

① Design and Selection of Elbow Structures

The structure design of the hyperbolic elbow is various. It can be divided into four-point type and five-point type according to the number of points of elbow hinge. And it is divided into diagonal and straight arrangement according to the direction of elbow bending. According to the direction of bending elbow turnover, it can be divided into two types: overturning and overturning. One of them can be selected for design.

② Kinematic analysis of elbow mechanism

According to the selected structure, mechanical and geometrical analysis is carried out to determine the mathematical relationship between the parameters. Expressions of characteristic quantities such as stroke ratio, mode-shifting speed and force magnification are analyzed. The with the help of MATLAB, the relationship between geometric parameters and target characteristic quantity is analyzed and several groups of slightly better solutions are determined.

③ Numerical analysis and motion simulation

The above parameter solutions and characteristic quantities are input into MATLAB to analyze the characteristic quantities, such as the relationship between the speed of movable template, acceleration, force amplification ratio and stroke. Meanwhile, the elbow structure can also be modeled in ADMAS or ANSYS. Then, dynamic analysis of the structure is carried out to obtain the optimal solution.

The design of the elbow mechanism is roughly described above, but the specific design forms are also very diverse. Due to the large number of parameters, the interaction is complicated. In actual design process, the optimum design must be carried out according to different requirements of closing mechanism.

In general, the design points of the clamping mechanism are as follows:

- ① To ensure reliable installation, fixing and adjustment of the molds;
- ② It can quickly open and close molds, safely close molds at low pressure and low speed and lock molds at high pressure according to injection molding requirements;
- ③ Meet the requirements of strength and stiffness;
- ④ Energy saving and consumption reduction.

(2) Design of ejection mechanism

The design of the ejection mechanism is closely related to the structure of the molds and products. The ejection methods include push rod ejection, push plate ejection and push piece plate ejection, etc. The corresponding ejection parts are push rod, push plate and push piece plate. There is no much to say about this part. This section

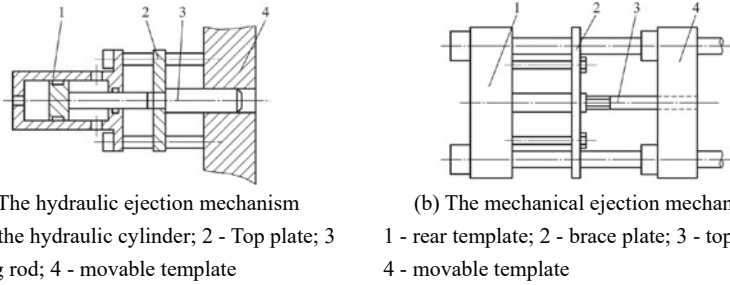


Fig. 4.47 Types of ejection mechanism

mainly introduces the design points of the ejection mechanism from the angle of ejection mode.

The ejection mechanism can be divided into hydraulic type and mechanical type according to the ejection mode.

The hydraulic ejection mechanism (Fig. 4.47a) relies on the ejection cylinder on the automatic template. Hydraulic pressure can be adjusted well and reset by itself, so it is widely used.

The mechanical ejection mechanism (Fig. 4.47b) is to demold the parts by utilizing the relative motion formed by the structure such as the top plate of the ejector rod and the movable template retracting when opening the mold. Although this structure is simple, its ejection force and reset are all inconvenient to control. Therefore, it is usually only used on small equipment.

(3) Design of tie rod

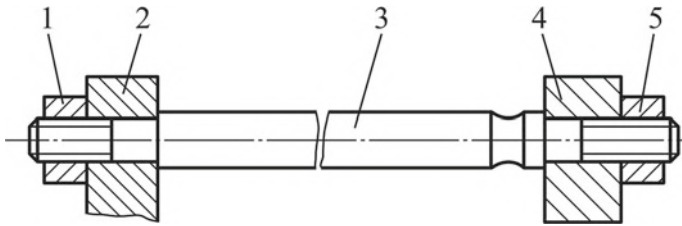
The pull rod is an important bearing component in the operation of the mold system and plays a guiding role in the movement of the movable template. Therefore, it plays an important role in precise control of the whole mold system. The mold rod can be divided into fixed structure and adjustable structure according to its connection to the template.

The structure of the fixed tie rod is shown in Fig. 4.48. The two ends are fixed by threads. Although the fixed structure is simple in design, it can not guarantee the installation accuracy of the mold. It is mostly used on small equipment.

The structure of the adjustable tie rod is shown in Fig. 4.49. Parallelism between the base of the template and the movable template can be adjusted. Although the structure is complex, the installation and action accuracy can be reliably controlled, so it is widely used.

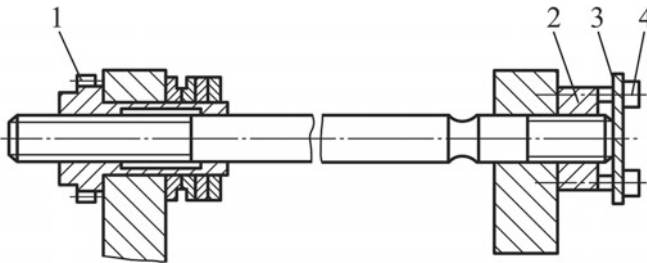
In addition to meeting the requirements of strength and stiffness, the structural design of tie rod should take full account of the form of closure structure, and its design points are as follows.

- ① Adequate abrasion resistance. The pull rod plays a guiding role and frequently slides relative to the movable template, so adequate wear resistance is required.



1- rear nut; 2 - rear template; 3 – pull-out; 4 - front template; 5- front nut

Fig. 4.48 Fixed tie rod



1 - one set of rear nuts; 2 - front nut; 3 - pressure plate; 4 - one bolt

Fig. 4.49 Adjustable tie rod

- ② Pay attention to eliminating stress concentration. A buffer tank is provided at the mold thickness section to prevent overload from damaging the closing mechanism and to improve fatigue resistance.

(4) Design of Modulation Mechanism

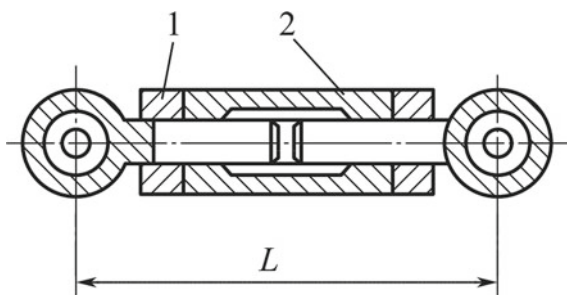
An injection machine often needs to mold different products. In order to install the molds of different thicknesses and extend the production range of injection molding machined products, a device adjusting the distance between the molds must be set, i.e. a molding device. In the technical parameters of the closing system of the injection molding machine, the maximum and minimum molding thicknesses are available. Adjustment of the maximum and minimum mold thicknesses is achieved by means of a mold adjusting device. The device can also adjust the closing force. For the direct press closing mechanism, the stroke of the movable template is determined by the stroke of the moving cylinder. The adjusting device is realized by means of the closing cylinder, and the adjusting stroke should be part of the movable template stroke, so no additional adjusting device is required. For the hydraulic-mechanical mode closing device system, the mode adjusting device must be set separately. This is because the working position of the elbow mechanism is fixed and the travel of the movable template cannot be adjusted.

At present, there are several forms of the mode adjustment mechanism which are widely used.

- ① **Mold adjusting device of threaded elbow bar type** This structure is shown in Fig. 4.50. While using, adjust the elbow length L by turning the adjusting nut with positive and negative buckle, thus realizing the adjustment of the mold thickness and closing force. This form has the advantages of simple structure, easy fabrication and convenient adjustment. However, the thread must bear the closing force, so the closing force should not be too large and the adjustment range is limited. It is mostly used in small injection molding machines.
- ② **Molding device of large nut type between movable templates** As shown in Fig. 4.51, it consists of two movable templates, left and right. The middle is threaded together. By adjusting the adjusting nut 2, the distance H between movable templates is changed, thus adjusting the thickness of the mold and adjusting the closing force. This form is easy to adjust, but needs to increase the length of the template and machine, mostly for small and medium-sized injection molding machines.
- ③ **Cylinder nut type mode adjustment device** As shown in Fig. 4.52, this structure is adjusted by changing the fixed position of the mold shifting cylinder. When in use, by turning the adjusting handle and the adjusting nut 2, the closing cylinder 1 generates an axial displacement. It causes the closing mechanism to move forward or backward along the pull rod, thus adjusting the mold thickness and closing force accordingly. This form is easy to adjust and is mainly suitable for medium and small injection molding machines.
- ④ **Mold adjusting device of tension rod nut type** There are many types of tension rod nut type adjusting device. At present, the mode adjustment form of large gear is mostly used, as shown in Fig. 4.53. The molding device is mounted on the rear template 1. During the mode adjustment, the rear template moves with the elbow linkage mechanism and the movable template, and the four rear nut gears 4 rotate synchronously under the drive of the large gear 3, which drives the rear template and the whole clamping mechanism to move along the axial direction. Adjust the distance between the movable template and the front template to adjust the entire mold thickness and closing force. This adjusting device has compact structure, reduces the length of axial dimension chain, improves the rigidity of the system, and is easy to install and adjust. However, the structure is complicated and synchronization accuracy is required. Handwheel drive is used in small injection molding machines, while common motor, hydraulic motor or servo motor are used in medium and large injection molding machines.

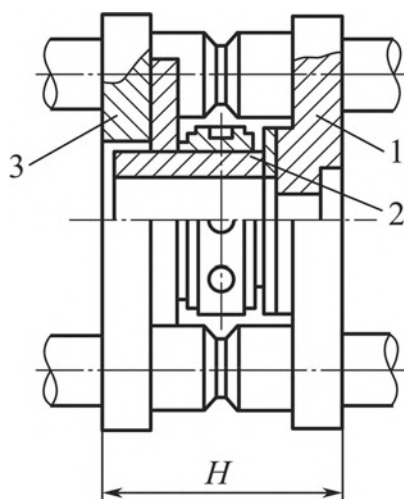
In addition, the standard parameter values of ZBG95003-87 can be consulted to determine the adjusting stroke. Some data are selected here for reference, as shown in Table 4.5.

Fig. 4.50 Molding adjustment device with threaded elbow



1 - adjusting nut; 2 - lock nut

Fig. 4.51 Molding device of large nut type between movable templates



1 - right-hand template; 2 - adjusting nut;
3 - left-hand template

4.5.3 Drives and Safety Devices

Previously mentioned that there are two main forms of injection molding machine drive: one is hydraulic, the other is electric.

Compared with hydraulic drive, electric drive has the following advantages: ① high transmission efficiency; ② Convenient disassembly and assembly, low maintenance cost; ③ Small area and light weight; ④ Low noise, no pollution, no fuel consumption.

However, because the hydraulic type is easier to realize the process control of pressure and speed and the centralized control of the machine, the action is more stable. And its shortcomings are constantly improving. So, the current injection

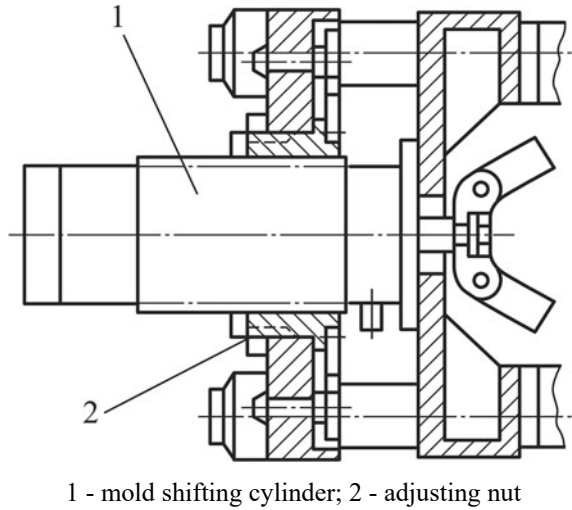


Fig. 4.52 Mode adjustment device of cylinder nut type

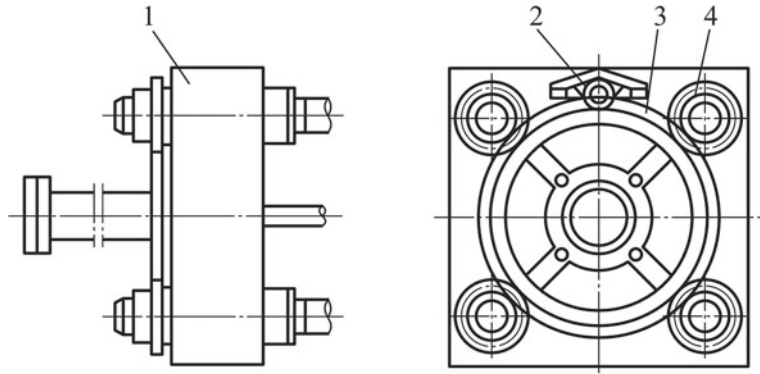


Fig. 4.53 Modulation device for large gear

Table 4.5 Mold-shifting strokes of various sizes/mm

Clamping force series/kN	500	630	800	1000	1250	1600	2000	2500	3200	4000
Effective spacing of tie rod $\geq$	280		315		355	400	450	500	560	630
Travel of moving template $\geq$	240	270		300	350	400	450	500	550	650
Maximum mold thickness	240	270		300	350	400	450	500	550	650
Minimum mold thickness	150	170		200	230	200	200	320	350	400

molding machine drive is still hydraulic. The safety device of injection molding machine is mainly to protect personal safety, machine and mold operation safety. The main contents are shown in Table 4.6.

Table 4.6 Protection contents of injection molding machine

Project	Measure	Protection content
Safety door of clamping device	① Electrical protection ② Electrical hydraulic protection ③ Electrical (hydraulic) mechanical protection	Only when the safety door is fully closed, can the clamping action be carried out
Safety of the operating part of the clamping mechanism	Add protective cover	Prevent people or objects from entering the moving parts
Over travel protection	Electrical or hydraulic travel limit	To prevent the hydraulic clamping device Processing too thin mold, or no mold case for clamping
Mold protection	① Trial mold clamping under low pressure and low speed ② Electronic monitoring	Try to close the mold to make sure there is no foreign matter, then press the pressure tightly to prevent foreign matter from crushing the mold cavity or producing defective products
Screw overload protection	① Over current protection of pre molding motor ② Mechanical safety protection ③ Heating of barrel at fixed time and temperature	Prevent the screw from overload damage caused by foreign matter or “cold start” in the plastic
Protection of heating cylinder and nozzle	Protection cover	Prevent heat burns
Screw metering protection	Double electrical protection and alarm	To prevent the metering stroke switch failure, and the screw continues to retreat caused by the accident
Working indication of heating ring	The indicator light indicates the position of the broken heating coil and gives an alarm	To prevent defective products or machine accidents caused by broken heating coil

(continued)

Table 4.6 (continued)

Project	Measure	Protection content
Maintenance of hopper level	The lower part of hopper is installed with electric contact or photoelectric level device	Prevent the normal operation of the machine from being damaged due to the lack of material in the hopper
Lubrication system	Lubrication point indication and alarm	To prevent the elbow mechanism from losing lubrication and causing accidents
Hydraulic system	Oil level and oil level indication and alarm	Maintain the normal working conditions of the hydraulic system
Working environment and noise	① Low noise pump and valve ② Low noise oil pressure piping ③ Increase the frame rigidity ④ Noise and noise	Elimination measures The noise of the whole machine should not exceed 85 dB (ZBG 95004-87)

4.6 Process Control of 3D Copier [12]

4.6.1 Core Principles of Product Accuracy Control

The PVT relation of polymer describes the change of specific volume of polymer material with the change of temperature and pressure. As the basic property of polymer, it is also used to explain the possible causes of warpage, shrinkage and bubbles in the processing of products. It plays an important role in the production, processing and application of polymers. The PVT data of polymer provide information about the compressibility and thermal expansion of polymer in the range of temperature and pressure. The computer simulation and control of injection molding process is based on the PVT relationship of polymer. It provides data, detection and control basis for the development of precision injection molding machine in China. It leads the development direction of precision injection molding.

Figure 4.54 shows the PVT curve of amorphous polymer and semi crystalline polymer. It can be seen from the figure that when the material temperature increases, the specific volume also increases due to thermal expansion; As the pressure increases, the specific volume decreases due to compressibility.

At the glass transition temperature point, the increase rate of specific volume becomes faster because the molecules have more degrees of freedom and occupy more space. Therefore, the obvious change of the slope of the curve can be seen in the figure. Thus, the transition temperature when the volume of the polymer changes suddenly can also be found by the PVT curve.

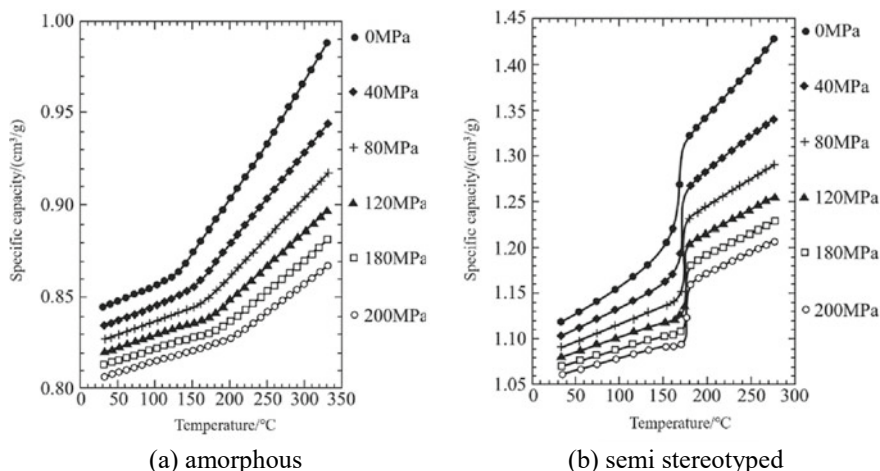


Fig. 4.54 PVT curve of polymer

In the process of temperature change, both amorphous and semi crystalline polymers will undergo crystallization or glass transition due to molecular thermal motion, which results in obvious volume change. However, the volume of semi crystalline polymer will change greatly due to the regular arrangement of particles in the crystallization process. Therefore, it can be seen that the PVT relations of amorphous and semi crystalline polymers are obviously different. At higher temperature, the specific volume of the semi crystalline polymer increases sharply when it enters the molten state. This is due to the fact that the crystal region with regular and fixed structure can move freely due to the influence of temperature.

Polymer PVT curves show the shrinkage characteristics of plastics during injection molding through specific volume changes. The influence of temperature and pressure on the specific volume of polymers can be seen from it. Information on polymer density, specific volume, compressibility, volumetric expansion coefficient, PVT equation of state, etc. can be obtained intuitively. The research on the relationship characteristics of polymer PVT can not only explain the phenomena related to pressure, density and temperature during injection molding, but also analyze the causes of warpage, shrinkage, air bubbles and other defects that may occur during product processing. So, it's available to obtain the optimum process conditions for polymer processing, and make the optimum process parameters more quickly and conveniently. It can also guide the control of injection molding process improve the control precision of injection molding equipment so as to produce high quality products.

The applications of polymer PVT relationships can be summarized in the following areas:

- ① Prediction blending type of polymer;

- ② Predict the service performance and service life of polymer materials and components based on free volume concept;
- ③ Estimate the change of chemical reaction in polymer melt with volume effect accompanying reaction;
- ④ Optimizing process parameters to replace some parameters established by operating errors or experience;
- ⑤ Calculating surface tension of polymer melts;
- ⑥ To study the parameters of state equation and reduce the relationship with molecular structure;
- ⑦ Study the properties of materials related to gases or solvents;
- ⑧ Research on the nature of phase transition.

PVT data reflecting the actual situation of polymer processing can make the rough results of computer simulation more accurate. The PVT curve of polymer describes the relationship between melt specific volume and temperature, and pressure, which is the basis of keeping the same quality of each molding product.

4.6.2 Process Control Methods for Product Accuracy

- (1) PVT relation characteristics and pressure variation of polymer during injection molding

In order to ensure the quality of molded products, it is necessary to master the specific volume change of polymer materials in the mold. The best way of pressure change in the process of material forming can be obtained by PVT curve. The PVT curve of polymer can also be expressed by a series of different mathematical expressions (PVT equation of state). Based on the injection molding process and the pressure change of polymer material, the changes of PVT relationship characteristics of polymer in the whole injection molding process are described in detail.

Figure 4.55 describes the polymer PVT relationship characteristic curve and mold cavity pressure curve. Point A is the starting point of the injection molding process, when the polymer stays in the front part of the screw in the barrel of the injection molding machine in a molten state. A-C is the injection stage. Point B is the starting point of the mold cavity pressure signal (at this time, the pressure sensor in the mold cavity contacts the melt for the first time), and then the pressure begins to increase. At point C, the injection stage is completed. Then, the molten polymer material freely fills the mold cavity, and enters the compression stage (C-D). At this stage, the mold cavity pressure rises rapidly to the highest value (point D). At this time, the injection pressure changes to the holding pressure and enters the holding stage (D-E). More polymer melt is pressed into the mold cavity to continue to replenish the gap caused by the decrease of cooling shrinkage volume of the first melt. This process is completed until the gate freezes (point E), at which the melt can no longer enter the mold cavity. Point E is the end point of packing, which is the freezing point of gate. In the remaining cooling stage (E-F), the melt in the mold cavity keeps a constant

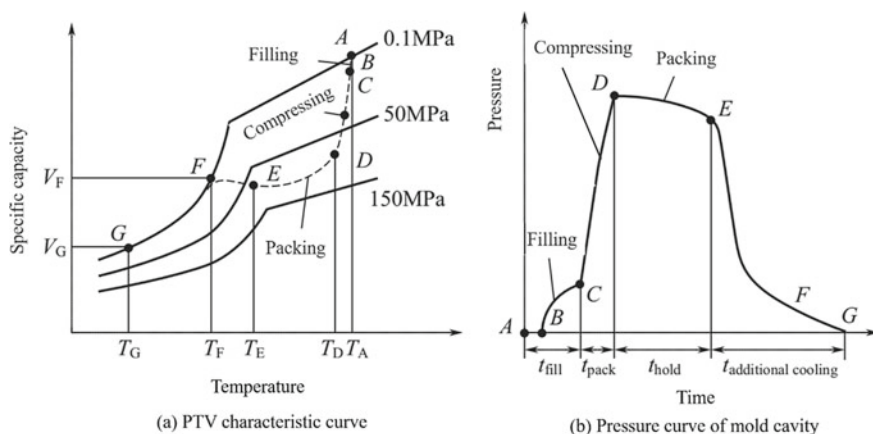


Fig. 4.55 Typical polymer PVT relationship characteristic curve and mold cavity pressure curve

volume and continues to cool, and the pressure decreases rapidly to normal pressure. This constant volume cooling stage is particularly important because it requires constant volume to obtain minimum orientation, residual stress and distortion. This stage plays a decisive role in the dimensional accuracy of forming. At point F, the product in the mold cavity can be formed without any restrictions. It can be ejected and further cooled to room temperature (F-G). The products undergo free shrinkage in F-G stage.

It can be seen that the final product size and quality is determined by the control of the packing process in the injection molding process. This is also the core content of injection molding process control. The control of packing process is mainly in E-F stage, which has a great influence on the quality of final products. Because point F is a variable that cannot be directly controlled in the process of injection molding, the control of point E becomes the core point of PVT relationship control in injection molding. The control of point E is affected by point D and D-E stage (i.e. the control of pressure transfer point and pressure holding process). Therefore, the injection molding process control is focused on the pressure maintaining process control.

(2) Principle of polymer PVT relationship characteristic control technology based on injection molding equipment

At present, the existing control methods of injection molding machine are aimed at the separate control of pressure (injection pressure, nozzle pressure, packing pressure, back pressure, mold cavity pressure, system pressure, clamping force, etc.) and temperature (barrel temperature, nozzle temperature, mold temperature, mold cavity temperature, hydraulic oil temperature, etc.). In the aspect of improving the control accuracy, it mainly focuses on the separate control of pressure and temperature, and does not consider the control of the relationship between material pressure and temperature.

The principle of polymer PVT relationship control technology, which is based on injection molding equipment, mainly controls the change of material specific volume (V) by controlling the relationship between pressure (p) and temperature (T) of polymer material, so as to obtain products with certain volume and weight. Therefore, under the condition of ensuring the separate control precision of pressure and temperature variables, and then ensuring the control precision of the relationship between pressure and temperature, the control precision of injection molding quality can be further improved on the whole. Thus, the “process variable control” can be raised to the level of “quality variable control”.

The control of pressure holding stage in injection molding process can be divided into three parts. It includes the control of v -use pressure transfer point from injection stage to pressure holding stage, the control of pressure holding end point and the control of the whole pressure holding process. It is very important for the molding quality of the products to set the turning point correctly and adopt the process control of subsection pressure holding. According to the PVT relationship control theory of polymer, the author team developed a series of injection molding process control technology. It includes melt pressure V/p pressure transfer, melt temperature V pressure transfer, melt pressure control at the end of holding pressure, melt temperature control at the end of holding pressure, on-line control technology of polymer PVT relationship characteristics, melt temperature control during holding pressure process and multi parameter combined control. At the same time, a special injection molding pressure maintaining process control system was developed to carry out the experimental research of related control technology.

Figure 4.56 shows the principle of polymer PVT relationship characteristic control technology based on injection molding equipment. Where p_n is the nozzle melt pressure. T_m is the melt temperature of the nozzle. p_{c1} is the melt pressure in the mold cavity at the far gate point. T_{c1} is the mold cavity melt temperature at the far gate point. p_{c2} is the melt pressure in the mold cavity near the gate point. T_{c2} is the mold cavity melt temperature near the gate point. T_c is the coolant temperature. P_h is the system oil pressure. S_o is the opening size of the servo valve, Y_r is the screw position, and V_r is the screw speed.

Figure 4.57 is the flow chart of polymer PVT relationship characteristic control system based on injection molding equipment. It mainly focuses on the control of injection molding pressure maintaining process, including the selection program of V/p pressure transfer, pressure maintaining process, pressure maintaining end point, time signal, screw position signal, pressure / temperature signal, etc.

4.7 Precision 3D Copier

The so-called precision plastic products generally refer to miniaturized and thin-walled plastic products. These products have high precision in size, weight, shape and function. Therefore, injection molding has higher requirements. The remarkable

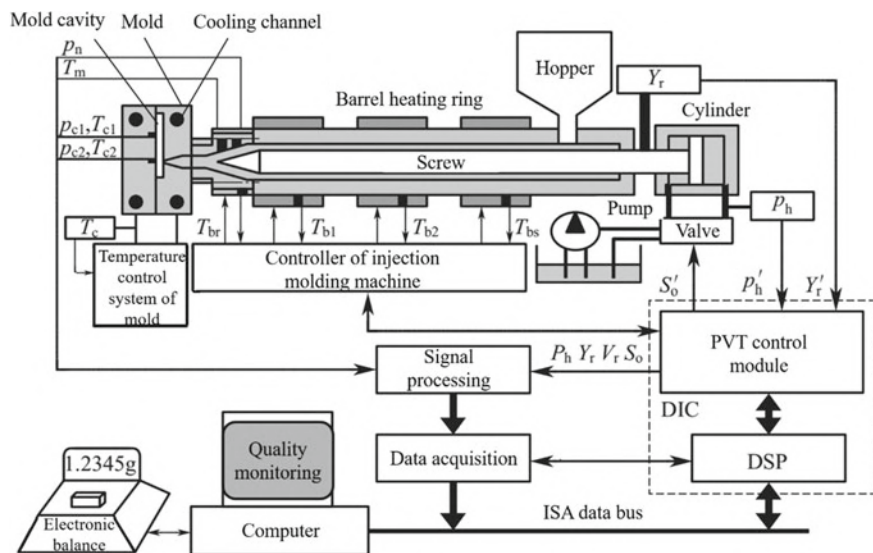


Fig. 4.56 Principle of polymer PVT relationship characteristic control technology based on injection molding equipment

characteristics of precision injection molding are high injection pressure, fast injection speed and strict temperature control. In order to ensure the normal production, it is necessary to improve the conventional injection molding machine and control some links effectively. It is mainly reflected in the following aspects [13, 14].

(1) Selection of raw materials

For precision injection molding technology, additives used in different plastics and the proportion, composition and category of polymers are different. And the formability and fluidity of the materials are also very different. Due to the miniaturization and thin-wall of precision products and the high-pressure and high-speed injection environment, the requirements for materials of precision injection molding technology are as follows [15]:

- ① It has good formability and fluidity, stable and uniform density and fluidity;
- ② It has high mechanical strength, good stability and strong creep resistance;
- ③ The internal stress of the material is relatively stable and small;
- ④ The shrinkage of plastics should be as small as possible.

Generally speaking, the commonly used precision injection molding materials are POM (polyoxymethylene), POM + CF (carbon fiber), POM + GF (glass fiber), PA (nylon), frpa66 (glass fiber reinforced nylon), PBT (polybutylene terephthalate), PC (polycarbonate) and other engineering plastics [16–18].

(2) High precision injection molding equipment

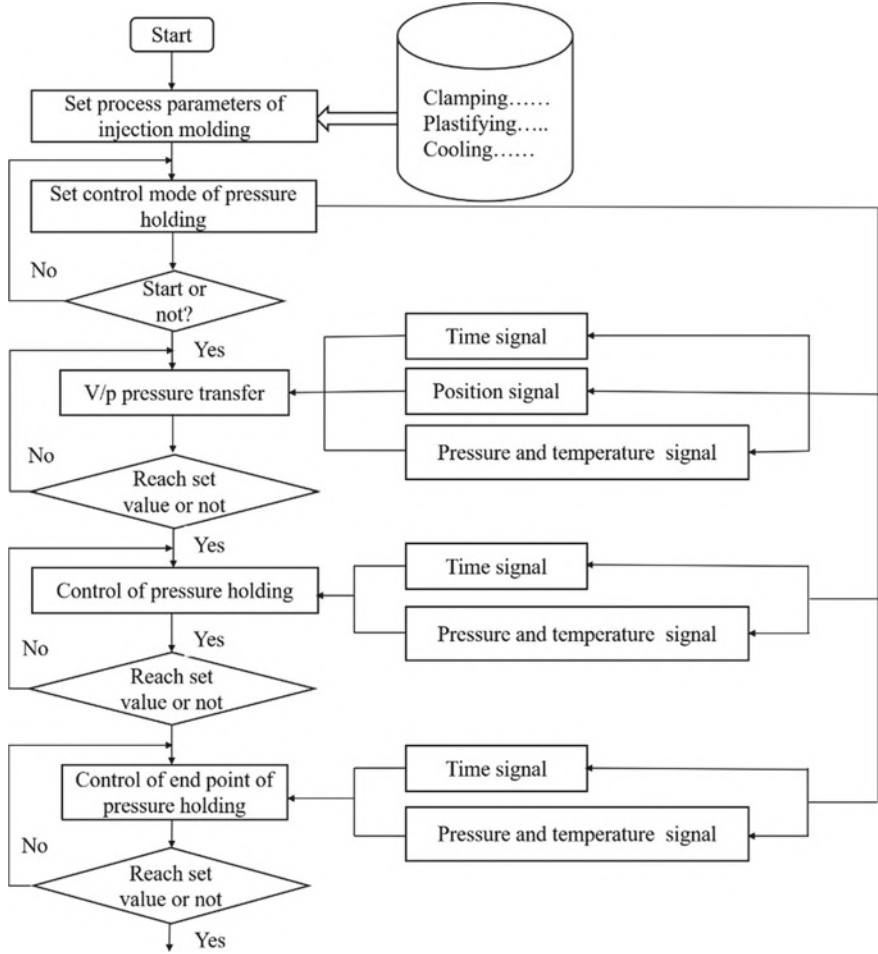


Fig. 4.57 Flow chart of polymer PVT relationship characteristic control system based on injection molding equipment

Precision injection molding machine in the injection equipment is mainly reflected in two aspects: the high-speed injection system and the high-precision clamping system.

① High-speed injection system

During the forming of thin-walled products, the viscous resistance and cooling rate of polymer melt entering the cavity increase with the decrease of the wall thickness of the products. Products are prone to defects such as underfilling, weld marks and stress concentration. It is an effective method to improve the temperature of barrel mold and injection speed in order to guarantee the precision of products. Increasing the temperature of the mold allows the polymer melt to have good flow properties

and is conducive to filling. However, it is needed to prolong the cooling time, thus prolonging the forming cycle of products, which is not conducive to improving production efficiency. However, the advantage of increased injection rate is more significant. The shear stress of polymer melt during high speed injection increases, the viscosity of polymer melt decreases, and shear thinning occurs. Therefore, the fluidity is enhanced, the filling time is shortened, and the production efficiency is improved. In addition, the pressure and temperature distribution of the product are uniform in high-speed injection molding, which can effectively reduce the warpage.

High speed injection molding equipment has been reported as early as the 1980s. So far, it has developed for more than 30 years, and now there are various forms of development. Generally speaking, the high-speed injection means that the injection speed is more than 300 mm/s. The ultra-high speed is as high as 800 mm/s. According to the different driving mode, high-speed injection machine can be divided into hydraulic type and fully electric type.

Hydraulic high-speed injection machine is equipped with energy storage in the hydraulic system to achieve high-speed injection. There is a rubber air bag inside the accumulator. The inside of it stores high-pressure gas, and the outside of it is high-pressure oil, which is connected with the hydraulic oil circuit. Before the injection, there is a pressure difference between the hydraulic oil circuit and the internal space of the accumulator. The internal pressure of the accumulator is lower than the oil circuit pressure, which makes the hydraulic oil charge into the accumulator and compress the air bag for energy storage. During injection, the air pressure in the airbag is higher than that in the hydraulic oil circuit. The airbag squeezes the hydraulic oil stored in the accumulator into the oil circuit. At this time, the flow of hydraulic oil in the oil circuit increases instantaneously, and the driving screw completes the high-speed injection [6].

Different from hydraulic high-speed injection machine, fully electric high-speed injection machine is no longer powered by hydraulic motor and oil cylinder, but driven by servo motor, synchronous belt and ball screw, as shown in Fig. 4.58. Because the dynamic response time of servo motor, encoder and driver is only a few milliseconds, the transmission accuracy of ball screw can reach micron level. Its transmission efficiency can reach 90%, which makes the electric injection machine has the advantages of fast response, high precision, energy saving and environmental protection.

In the field of fully electric high-speed injection, Japan has always been at the leading level, and the development is very rapid. According to statistics, 80% of Japan's domestic injection machines are fully electric [19]. Figure 4.59 is a picture of the products produced by FANUC company in Japan α -S250iA fully electric injection machine. The highest injection speed can reach 1200 mm/s, which has good molding performance for ultra-thin plastic products such as light guide plate. Generally, in the injection process, fully electric high-speed injection machine uses the servo motor to drive screw through synchronous pulley and ball screw. This machine abandons the synchronous pulley and uses the motor directly connected with the ball screw to drive. It can reduce the moment of inertia of the injection system and improve the response performance. The company has a kind of super

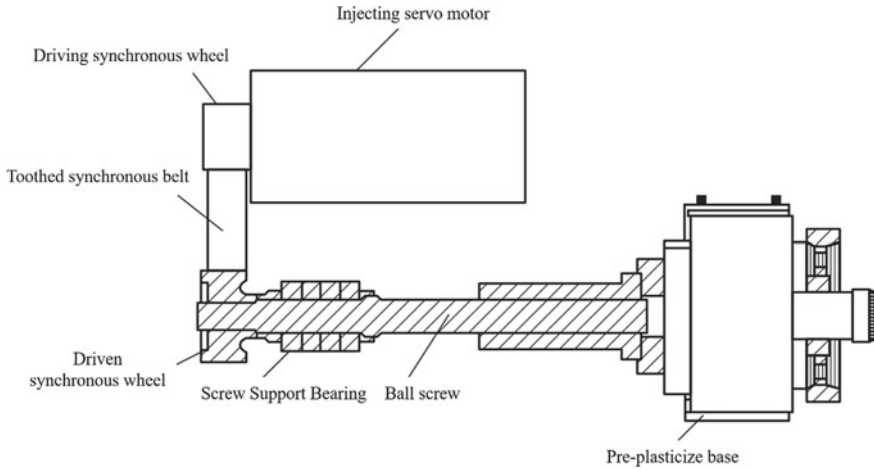


Fig. 4.58 Driving principle of fully electric high speed injection machine

high speed injection machine called SUPERSHOT 100i. It is driven by four high-power linear motors. The maximum injection speed and acceleration are 2000 mm/s and 17 g respectively.

In fact, the full electric form also has some problems in high-speed occasions. For example, when the injection speed is too high, the full electric ball screw has serious wear and heat, rapid wear and so on. But in general, the electric type is superior to the hydraulic type in the aspects of high speed, high precision and fast response time. In addition, the electro-hydraulic compound driving injection with electric injection and hydraulic pressure maintaining is also a development trend in the future. It is

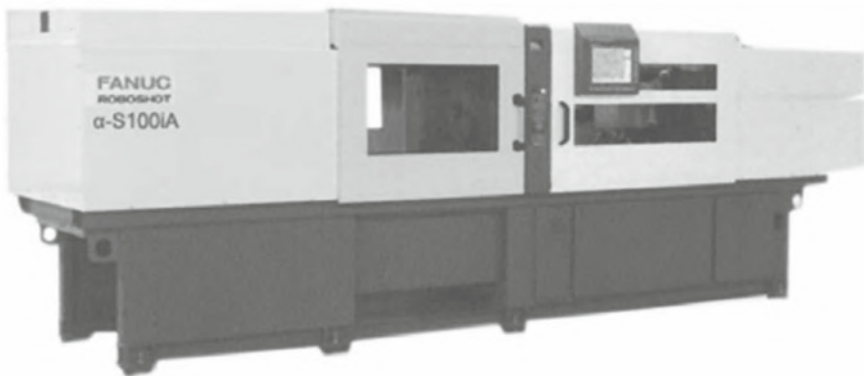


Fig. 4.59 α-S250iA fully electric injection molding machine

more possible to replace the combination of servo motor and ball screw with linear motor for linear injection.

② High precision of clamping system

The clamping accuracy is one of the most important technical difficulties in forming micro thin-walled products. Poor clamping accuracy will lead to uneven thickness. This effect may not be obvious in thick wall products, but when the wall thickness of the product is only 0.1~0.2 mm, the wall thickness difference of 0.02~0.03 mm will also seriously affect the molding of the product, such as shortage of materials in some places, flash in some places, etc. In the first mock exam, the situation is even more serious. Operators often only see the phenomenon of flash, but don't understand that the essence of flash is the unbalanced clamping force of the equipment. So, they often simply increase the clamping force to solve the problem. The increase of clamping force means that the hinge pin shaft is accelerating wear for the elbow bar clamping mechanism. It will lead to the decline of clamping force and further decline of clamping accuracy. In serious cases, it will lead to broken pin shaft, broken pull rod, cracked formwork, etc. In addition, when the elbow bar device of traditional elbow bar injection molding machine is in the low-pressure clamping area (Fig. 4.60), it is just the amplification area of the elbow bar force. The mold moving force is far beyond the set value after amplification, and it is unstable, so it is very unreliable. Therefore, the low-pressure mold protection is not reliable, and it is very likely that individual products will not eject. Finally, the products left on the mold will damage the mold under high-pressure mold locking. For various reasons, the traditional three plates elbow bar injection molding machine is difficult to meet the requirements of high precision clamping. Therefore, in order to improve the clamping accuracy of the injection molding machine, a more compact two plates injection molding machine appears [20, 21].

Two plates injection molding machine can be divided into two plates compound type and two plates direct pressing type. Due to the increase of mechanical action, the cycle of opening and closing mold is prolonged. Therefore, it is not suitable for

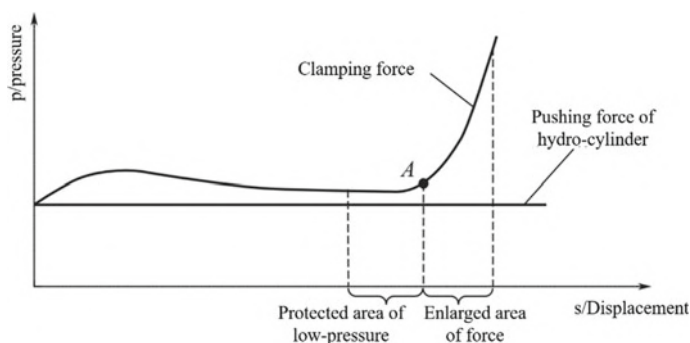


Fig. 4.60 Pressure-displacement curve of toggle mechanism during clamping

small and medium-sized injection molding machine. It is the development direction of large plastic parts production. And the two plates direct pressing type does not need to increase the mechanical action before the high-pressure mold locking, so it has high efficiency and is suitable for the production of small products.

Figure 4.61 shows a direct pressing two plates clamping mechanism. The clamping device adopts the form of four cylinders direct lock. A mold shifting cylinder is arranged in the piston rod (i.e. the pull rod) of a group of diagonally arranged mold locking cylinders, while the other diagonal clamping cylinder is internal circulation cylinder. The mold locking sides of the four mold locking cylinders are communicated with each other. When moving the mold, the mold moving action is realized by the mold moving cylinder set diagonally. The hydraulic oil on both sides of the piston of the mold locking cylinder realizes the internal large circulation of the hydraulic oil of the mold locking system. It is completed through the internal circulation clamping cylinder and the communication channel of four clamping cylinders. During the mode locking, the valve core of the internal circulation mode locking cylinder is controlled to close through the valve control oil circuit. Four clamping cylinders work at the same time to achieve the rated clamping force.

Figure 4.62 shows the clamping process of the two plates compound clamping mechanism. It can be seen from the figure that, compared with the toggle mold closing, the force at 8 points of 4 corners of the mold is almost equal in the two plates mold closing. In addition, the parallelism error of the two plates mold closing is almost zero. In high-pressure mold locking, it can be adaptive according to the accuracy of the mold. Therefore, the precision and efficiency of the micro thin-walled products are much higher than that of the elbow bar.

However, compared with the three plates machine, the two plates machine depends on four clamping cylinders for clamping, which increases the energy consumption and slows the clamping speed. The requirements for structural design and motion

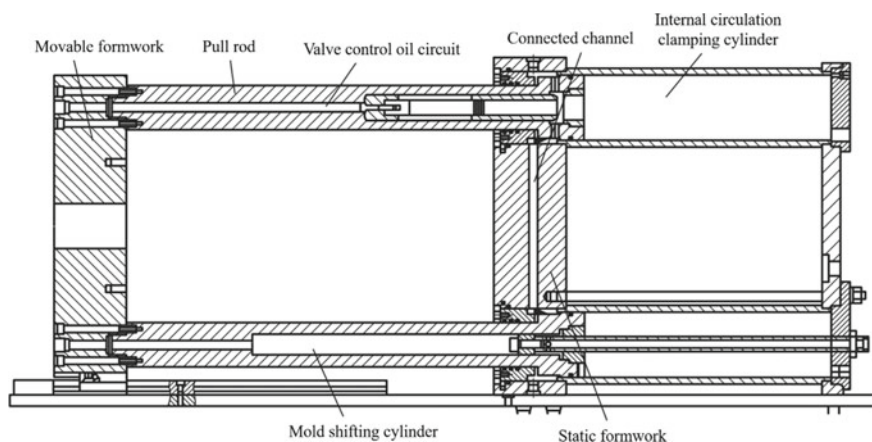


Fig. 4.61 Two plates direct pressing clamping mechanism

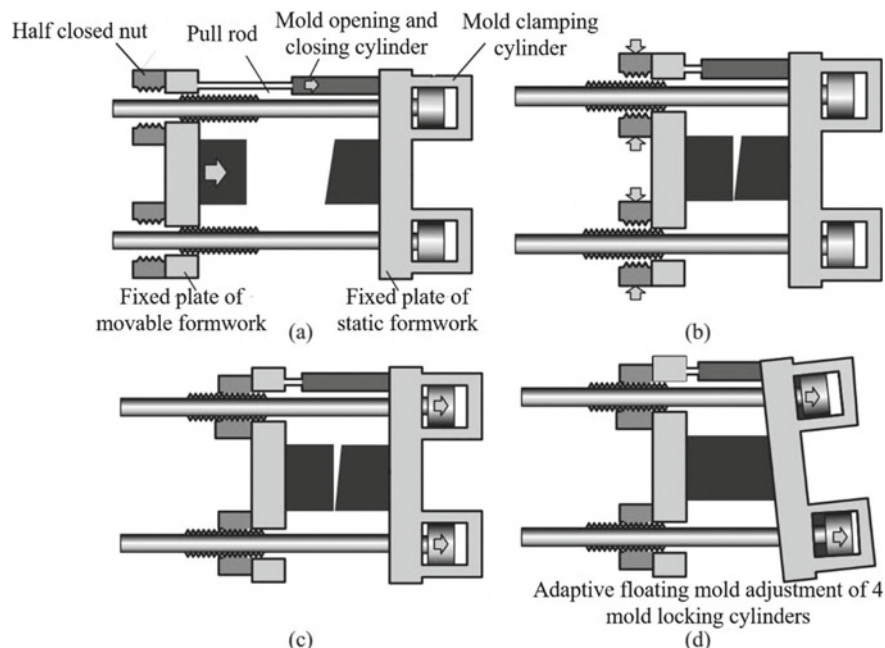


Fig. 4.62 Clamping process of two plates compound clamping mechanism

guidance of movable formwork are high, and the requirements for design, manufacturing, installation and maintenance are high. And the hydraulic system should complete the actions of mold opening, mold closing and high-pressure mold locking, which is more complex than the elbow bar type. All these increase the cost of the injection molding machine, making the price performance of the two plates machine is not high. Therefore, it is less used in minicomputers and mainly develops in the direction of “mainframe” [22, 23].

Considering the advantages and disadvantages of the toggle three plates machine and the low cost performance of the two plates machine, the author’s team has developed a new generation of precision three plates injection molding machine (Generation 2.0, G2.0). It not only retains the advantages of the traditional three plates machine, but also makes up for its low clamping accuracy. And adaptive “zero gap” clamping can be realized. There is no need to adjust the mold, which avoids the difficulty of adjusting the parallelism of the traditional three plates machine. Meanwhile, the force is balanced, which can effectively protect the pull rod and mold, and improve the service life of the pull rod and mold.

The clamping device of the machine is still a double toggle mechanism, which retains the advantages of the toggle mechanism. The difference from the traditional three plates machine is that an automatic adjustment device for the parallelism is set at the movable template, as shown in Fig. 4.63. It can effectively eliminate the gap between the movable and static templates in the process of mold closing, and

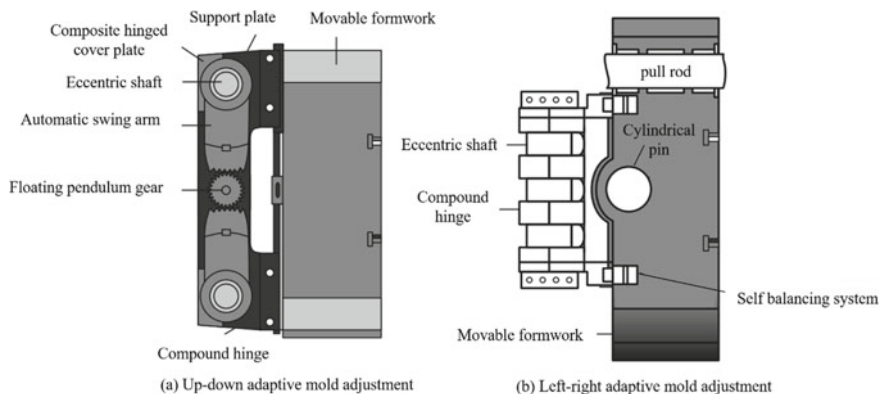


Fig. 4.63 Automatic adjustment device for parallelism of movable template

realize the adaptive “zero gap” mold clamping. Mold adjustment is mainly divided into up-down adaptive mold adjustment and left-right adaptive mold adjustment.

The principle of up and down direction adaptive mold adjustment is shown in Fig. 4.64. When there is a gap of the movable template or the static template due to inclination, the contact point of the movable template is subjected to force during mold clamping and transmitted to the eccentric shaft through the composite hinge. The automatic swing arm swings under the action of lever principle. Then it drives the floating gear to rotate, which makes the automatic swing arm on the other side swing, and finally leads to the deflection of the template. The left-right adaptive mold adjustment mainly depends on the cooperative action of cylindrical pin and self-balancing system. When the left and right direction of the template is deflected, the movable template will rotate around the cylindrical pin to adapt to the deflection of the template. Figure 4.65 shows the comparison between the up-down mold adjustment of the traditional three plates machine and the new three plates machine. When there is a gap between the movable and static formwork, the traditional three plates machine mainly deforms the four pull rods by rotating the four mold adjusting nuts of the static formwork so as to adjust the parallelism of the formwork. In this way, the mold adjustment structure is complex, the mold adjustment is difficult, and the formwork parallelism is difficult to ensure. Moreover, the pull rod and formwork are easy to fracture and the clamping accuracy is low. The new three plates machine adjusts the mold adaptively through the mechanical floating of the movable template. The formwork has uniform stress and high clamping accuracy, which can effectively protect the mold, especially when the mold cost is higher than the production machine.

The core structure of the up-down mold adjusting component is the eccentric shaft, and the structural forms of the lever are diverse. Figure 4.66 shows two forms of up-down adaptive mode adjustment. One is a center gear type, and it transmits and limits the torque of the eccentric shaft through the meshing transmission of large

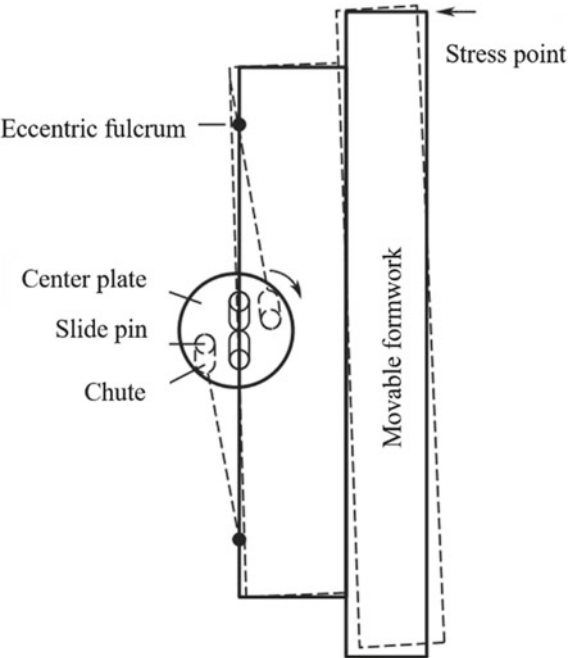


Fig. 4.64 Principle of adaptive mold adjusting mechanism

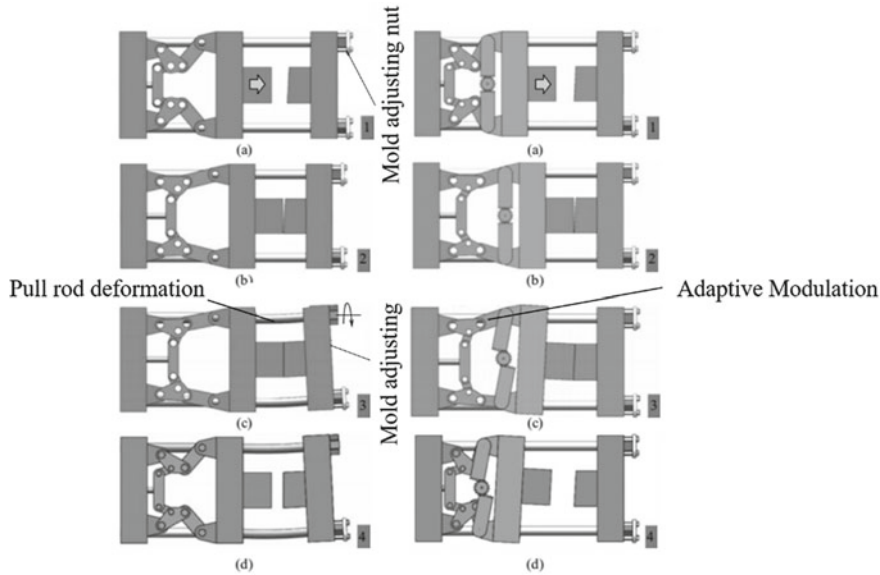


Fig. 4.65 Comparison of mold adjustment between traditional three plates machine (left) and new three plates machine (right)

and small gears. The other is rack and pinion type, which transmits and limits the torque of variable spindle through rack and pinion meshing [24, 25].

(3) Precise control of injection molding process

The process conditions affecting the quality of precision injection products can be divided into pressure, temperature and time, including injection pressure, back pressure, screw speed, injection speed, barrel temperature, holding pressure and time, multi-level control, cooling time, parts ejection, etc. In order to obtain high-performance and high-precision injection plastics, the direct measurement and control of material parameters (PVT parameters) in mold cavity has become a hot research topic. PVT is covered in Sect. 4.6 of this chapter.

Under the background of national strategy of “Industry 4.0” and “Made in China 2025”, intelligent application level of “3D copying” will be further improved by integrating molding equipment with intelligent manufacturing and cloud terminals, based on intelligent sensing and bearing large data.

Its intelligence level is mainly reflected in the following aspects: first, the degree of automation, such as automatic mold changing, automatic feeding, automatic parts taking, automatic trimming, etc. Secondly, centralized control and management, such as centralized feed, centralized water supply and power supply, multi-equipment common mold changer, unmanned injection molding workshop, etc. Third, large data and information platform, such as information exchange between injection molding machine group and manufacturers and customers, automatic diagnosis and control, remote diagnosis and control, product information traceability system, etc.

Define the standard process path for product quality on the polymer PVT characteristic [26, 27] curve as shown in Fig. 4.67. Through real-time on-line monitoring of melt temperature (T), pressure (p), specific volume (V) changes in the mold cavity, process fluctuations caused by changes in environmental conditions or viscosities are automatically identified and compared with the standard forming process path of product quality. If deviation occurs, the program will automatically adjust according to the PVT characteristics of the polymer melt and take appropriate measures. And it can significantly improve product repeatability and reduce scrap rate. Finally, in a real sense, on-line diagnosis and self-healing regulation of defects in injection molding products are realized.

Many injection machine manufacturers also include product information traceability systems in their equipment. It records all quality-related processing data, such as heating curves, injection pressure curves, cavity pressure curves, etc., and generates corresponding two-dimensional codes. Then it is printed on each product by means of 3D printing or laser engraving, and the “ID” is set for each product, as shown in Fig. 4.68. Customers can query and track the processing data of each component globally via mobile phones, tablets or desktops.

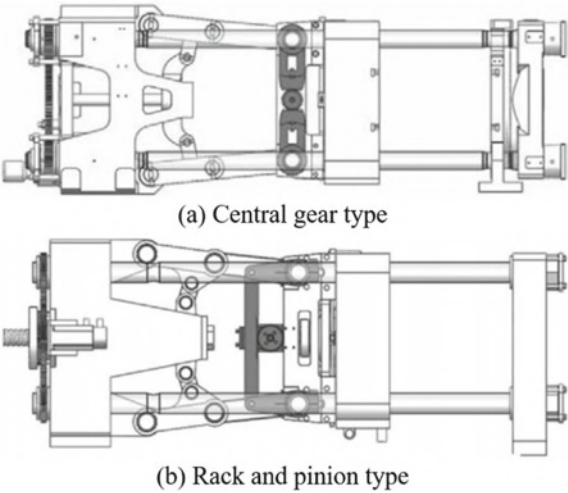


Fig. 4.66 Up-down adaptive mold adjustment in directions

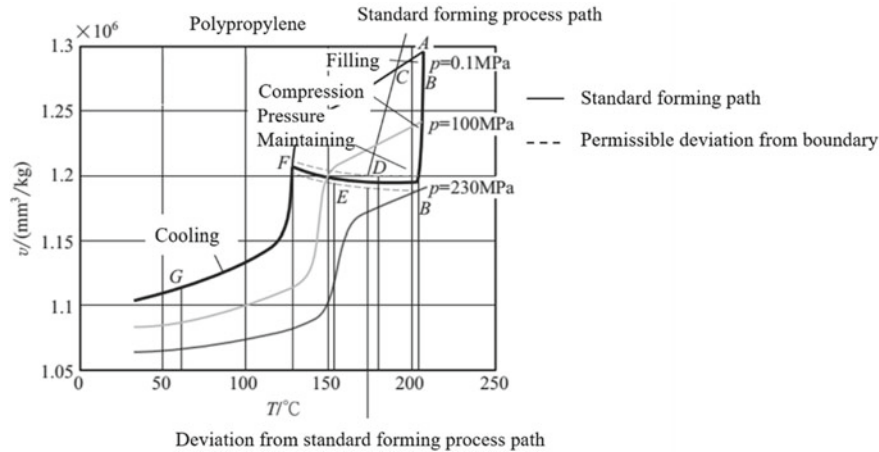


Fig. 4.67 On-line diagnosis and self-healing control of injection defects

Fig. 4.68 Product quality identity ID



QR code of product Information

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Chapter 5

Materials and Defect Analysis for Polymer 3D Copying



Abstract Injection molding is an important processing method to produce plastic products with complex shape, accurate size and insert. The three basic elements of injection molding industry are plastic raw materials, processing aids and plastic processing machinery. Plastics (polymers) are the main raw materials that can be used for injection molding, and the amount of plastics used for injection molding accounts for about 30% of the total plastic industry. Polymers are mainly composed of synthetic or natural polymer compounds, under certain temperature and pressure, it can be molded into a certain shape, when the external force is released, it can still maintain its shape at room temperature.

5.1 3D Copying Materials

5.1.1 *Classification of 3D Copying Materials*

Injection molding is an important processing method to produce plastic products with complex shape, accurate size and insert. The three basic elements of injection molding industry are plastic raw materials, processing aids and plastic processing machinery. Plastics (polymers) are the main raw materials that can be used for injection molding, and the amount of plastics used for injection molding accounts for about 30% of the total plastic industry. Polymers are mainly composed of synthetic or natural polymer compounds, under certain temperature and pressure, it can be molded into a certain shape, when the external force is released, it can still maintain its shape at room temperature. Polymers are characterized by huge molecular weight, unique properties and various forms of processing methods. Compared with traditional materials (such

as metal materials), the polymers have lower density, they are easy to process and can be molded at lower temperature. These make polymers widely used today.

(1) Thermoplastic for injection

There are several kinds of thermoplastics for injection.

- ① Polyolefin polymer: It generally refers to homopolymers and copolymers of ethylene, propylene and butene, the main varieties include polyethylene with different densities (LDPE, HDPE, MDPE, LLDPE) and polypropylene (PP). In the application fields of automobile parts and industrial parts, the use of modified polypropylene injection products is increasing.
- ② Styrene polymer: Such as polystyrene (PS), styrene acrylonitrile copolymer (AS), acrylonitrile butadiene styrene copolymer (ABS), etc.
- ③ More than 70% of nylon (PA) used for industrial parts are injection molded products.
- ④ Other thermoplastics: polyvinyl chloride (PVC), polymethylmethacrylate (PMMA), cellulose ester and ether plastics, polycarbonate (PC) and so on are processed by injection.
- ⑤ New special engineering plastics for injection: with the development of high-tech industry, the requirements for heat resistance and high temperature resistance of plastic products are more stringent, which promotes some special engineering plastics—high temperature resistant resin injection products' development, such as polyimide (PI), polysulfone (PSF), polyphenylene oxide (PPO), polyphenylene sulfide (PPS), polyether ether ketone (PEEK), thermotropic liquid crystal polymer (LCP), polyethyleneimine (PEI), polyoxymethylene resin (POM), etc. These materials have special requirements in injection process and mold structure because of their high melting point and high viscosity. Special engineering plastics account for about 5% of the total thermoplastic engineering plastics.

(2) Thermosetting plastics for injection

Thermosetting plastics are characterized by not only physical state changes, but also chemical changes during heating, and this change is irreversible. So far, almost all thermosetting plastics can be injection molded, but the most used is phenolic plastics. In addition, thermosetting resins used for injection molding also include urea formaldehyde resin, melamine formaldehyde resin, diphenyl phthalate resin, alkyl resin and epoxy resin. In the process of injection molding, the prepolymer or reactant with reaction group has cross-linking reaction under the action of heat, and its structure changes from linear to body shape. Therefore, the injection molding process and equipment of thermosetting plastics are quite different from those of thermoplastics.

The traditional thermosetting plastics are mainly compression molding and transfer molding. The compression molding process has the characteristics of complex operation, long molding cycle, low production efficiency, easy mold damage, easy waste products and unstable quality. It is a manual operation with strong physical strength and high cost. After the 1960s, the United States initiated

the thermosetting plastic injection molding process for the problems existing in the compression molding process. It was put into practical production in 1963. On this basis, the application of thermosetting plastic runner less injection molding process promoted the development of thermosetting plastic molding. The development and perfection of injection molding of thermosetting plastics promote the development of thermosetting plastics, it is widely used in electrical and electronic, instrumentation, chemical industry, textile, automobile, construction, machinery, light industry, military industry, aerospace and other departments.

(3) Elastomer for injection

Thermoplastic elastomer has the dual characteristics of plastic and rubber. It exhibits elasticity similar to vulcanized rubber at room temperature and plasticity similar to thermoplastic at high temperature. Therefore, it can be processed by injection. Thermoplastic elastomers commonly processed by injection molding methods include polyolefin thermoplastic elastomer (TPR), such as propylene ethylene propylene rubber copolymer, ethylene butyl rubber graft copolymer, etc.; Styrene thermoplastic elastomers, such as styrene butadiene styrene block copolymer (SBS), acrylonitrile butadiene styrene graft copolymer (ABS), etc.; in addition, there are polyester thermoplastic elastomers, polyurethane thermoplastic elastomers, etc.

At present, rubber products used for injection molding mainly include sealing rings, damping pads, air springs and shoes, as well as rubber products used for injection tire products. Injection rubber should go through two stages: plasticization injection and hot pressing vulcanization. Therefore, its injection process, equipment and mold structure are very different from plastics. Rubber for injection includes natural rubber, CIS polybutadiene rubber, methyl styrene butadiene rubber, chloroprene rubber, nitrile rubber, etc.

(4) Composites for injection

For injection molding materials, it can be pure polymers or mixtures with polymers as main materials and various additives as auxiliary materials. The purpose of adding auxiliary materials is to improve the mechanical properties and processability of polymers, or to save raw materials to improve economic benefits.

Plastic modification is one aspect of polymer material modification, including chemical modification and physical modification. Chemical modification refers to the chemical methods such as copolymerization, grafting, block, cross-linking or degradation to make plastic products have better properties or new functions. Physical modification is carried out in the process of plastic processing, there are usually three methods: filling, reinforcement and blending. Filling modification is to add inorganic filler or organic filler in the process of plastic molding, so as to reduce the cost of plastic products and achieve the increment. Reinforcement modification is to add mica sheet, glass fiber, carbon fiber, metal fiber, boron fiber and other reinforcement sets to plastics, which can greatly improve the mechanical and thermal properties of plastic products. Blending modification is to blend two or more plastics with different properties under a certain temperature and shear stress according to an appropriate proportion to form a plastic with the advantages of each plastic.

Modified composites for injection include modified general plastics, modified general engineering plastics and modified special engineering plastics.

- ① Modified general plastics. For example, the mechanical properties and heat resistance of thermoplastic PP, PE, PS and PVC have been greatly improved by means of filling, strengthening and foaming, and are developing in the direction of replacing engineering thermoplastic. PP can be modified not only by glass fiber and carbon fiber, but also by block copolymerization, composite technology and alloying technology. Engineering grade polystyrene (PS) has excellent impact resistance. Its impact strength is close to that of intermediate ABS, and maintains good toughness and appearance quality. Glass fiber reinforced PVC has high strength, flame retardant and easy processing.
- ② Modified general engineering plastics. Through modification, the functional characteristics of general engineering plastics are given to meet different needs, such as using high resilience elastomer to improve the impact resistance of general engineering plastics. Amorphous plastics were blended with general plastics to improve the processability and chemical resistance of the materials. In addition, the general engineering plastics are blended with each other to realize alloying, which can also give play to the performance advantages of each component. For example, PC/ABS alloy solves the defect of high viscosity of PC melt, reduces the cost of PC, and greatly improves the impact strength, stress cracking, notch sensitivity and fatigue resistance of PC. PA66/modified polyolefin elastomer alloy overcomes the disadvantage of low impact strength of nylon and maintains the properties of nylon such as chemical corrosion resistance, wear resistance and not easy to warp. POM/polyurethane elastomer alloy overcomes the disadvantages of narrow temperature range and poor heat stability of POM molding, and maintains the original wear resistance, flux resistance and fatigue resistance of POM. PC/PBTP/polyurethane elastomer alloy overcomes the disadvantages of stress cracking and solvent cracking of PC in gasoline chemical medium environment. PPO/PS alloy overcomes the disadvantage of too high viscosity of PPO melt, and the price also decreases significantly. PPS/PTFE alloy solves the problem that PPS has high melt flow rate and is difficult to be molded directly. It can still maintain high mechanical properties above 300 °C.
- ③ Modified special engineering plastics. PTFE, PI, PPS, PSF, PAR, PEEK, LCP, etc. usually have outstanding heat resistance, superior mechanical properties, good chemical resistance and wear resistance, but poor comprehensive properties. These materials are usually modified by filling and blending technology. For example, RTP company used glass fiber or carbon fiber to strengthen and modify thermoplastic polyimide (TPI), and its modified products have excellent heat resistance. LNP engineering plastics Europe used 60% glass fiber to modify PES, which not only improves the rigidity, but also simplifies the cost. The material has excellent chemical resistance, electrical insulation and mechanical properties, and has flame retardancy. The material has excellent chemical resistance, electrical insulation and mechanical properties. Hoechst company of Germany adopted 30 or 40% glass fiber reinforced LCP, the price is 15–40% lower than

that of ordinary LCP, and its physical properties are basically unchanged. The material has good heat resistance and dimensional stability.

(5) Composites for injection

The materials used for injection molding are not limited to polymers, but also include some metal materials (including magnetic materials). Metal powder injection molding (MIM) is a technology to manufacture metal products by degreasing (decomposing the adhesive) and sintering after injection molding with the mixture of metal fine powder and resin or paraffin (adhesive). It is a composite manufacturing process integrating powder metallurgy and plastic injection molding. Compared with powder metallurgy, it can use finer metal powder, so it can promote sintering, produce high-density materials, greatly improve product performance, and produce small metal parts with complex shape and higher precision.

Magnetic materials, especially permanent magnetic materials, as one of the important material bases for the existence of high-tech industry in the information society, show people their broad application prospects. The rapid development of electronic technology puts forward new requirements for magnetic materials. Magnetic components require complex shape, miniaturization, high dimensional accuracy, batch production, high yield and low cost. However, the magnet is hard and brittle, and its shape is limited. However, MIM technology can meet its requirements and manufacture high-performance magnetic components. Injection molding of magnetic materials includes two aspects: bonded permanent magnet injection molding and sintered magnet injection molding. Permanent magnet materials used for injection molding mainly include Nd-Fe-B system, samarium cobalt system and ferrite. Soft magnetic materials mainly include blunt iron, aluminum silicon iron, manganese zinc iron and nickel zinc iron. Starting from the use requirements of magnetic materials, the impurity content should be strictly controlled. According to the requirements of injection molding process, the average size of magnetic particles should be greater than 10 μm . The shape shall be spherical. Because small spherical magnetic particles are easy to mix evenly with plastic adhesive, it is conducive to the flow of molten plastic and full mold cavity.

(6) Injection plastic additives

Plastic additives, also known as plastic additives, are closely related to the plastic industry. There are many kinds of classification methods of plastic additives. The more common method is to classify according to the function of additives. In the category with the same function, it is often further subdivided according to the action mechanism or chemical structure type.

- ① Plasticizer. Plasticizer is a kind of assistant that increases the plasticity of polymer resin and endows products with softness. It is also the plastic assistant with the largest production and consumption so far. Plasticizers are mainly used in PVC soft products, and are also widely used in polar plastics such as cellulose.
- ② Heat stabilizer. Unless otherwise specified, heat stabilizer refers to the stabilizer used in the processing of PVC and vinyl chloride copolymer. Polyvinyl chloride

and vinyl chloride copolymer are heat sensitive resins. They are very easy to release hydrogen chloride during thermal processing, which will lead to thermal aging degradation reaction. Heat stabilizers generally achieve the purpose of thermal stabilization by absorbing hydrogen chloride, replacing active chlorine and double bond addition.

- ③ Processing modifier. Processing modifiers in the traditional sense almost specifically refer to the modifying additives used in the processing of hard PVC to improve the plasticization performance, the viscoelasticity of resin melt and the melt flow of resin. These additives are mainly acrylate copolymer (ACR), which plays an outstanding role in the processing of hard PVC products. The concept of process modifier in modern sense has been extended to polyolefin (such as linear low density polyethylene LLDPE), engineering thermoplastic resin and other fields. It is expected that there will be newer and wider varieties of processing modifiers after metallocene resins are put into use in the next few years.
- ④ Impact modifier. Broadly speaking, additives that can improve the impact resistance of hard polymer products are collectively referred to as impact modifiers. The traditional impact modifier is basically based on the elastic toughening theory, and almost all the compounds involved belong to various copolymers and other polymers with elastic toughening effect.
- ⑤ Flame retardant. Most plastic products are flammable, which brings many hidden dangers to the application safety of their products. Accurately speaking, it is more appropriate to call flame retardant as flame retardant, because “flame retardant” includes flame retardant and smoke suppression, which is broader than the concept of flame retardant. However, for a long time, people have been used to the concept of flame retardant, so the flame retardant referred to in the current literature is actually the general name of flame retardant and smoke suppression additives. Flame retardants can be divided into additive flame retardants and reactive flame retardants according to their use mode. According to different chemical composition, flame retardants can also be divided into inorganic flame retardants and organic flame retardants.
- ⑥ Antioxidant. Additives with the main function of inhibiting the thermal oxidative degradation of polymer resins belong to the category of antioxidants. Antioxidants are the most important type of plastic stabilizing additives. Almost all polymer resins are involved in the application of antioxidants. According to the action mechanism, the traditional antioxidant system generally includes main antioxidant, auxiliary antioxidant and heavy metal ion passivator.
- ⑦ Light stabilizer. Light stabilizer, also known as ultraviolet stabilizer, is a kind of stabilizing agent used to inhibit the photooxidative degradation of polymer resin and improve the weather resistance of plastic products. According to different stabilization mechanisms, light stabilizers can be divided into light shielding agents, ultraviolet absorbers, excited state quenchers and free radical trapping agents.
- ⑧ Filling and reinforcing system additives. Filling and strengthening is an important way to improve the mechanical properties of plastic products and reduce the

matching cost. The reinforcing materials involved in the plastic industry generally include glass fiber, carbon fiber, metal whisker and other fibrous materials. Filler is an incremental material with low matching cost. In fact, it is difficult to distinguish between reinforcing agents and fillers, because almost all fillers have reinforcing effects.

- ⑨ Antistatic agent. The function of antistatic agent is to reduce the surface resistance of polymer products and eliminate the electrostatic hazards that may be caused by electrostatic accumulation. According to different ways of use, antistatic agents can be divided into two types: internal addition type and coating type.
- ⑩ Lubricants and release agents. Lubricant is a processing modification additive used in polymer resin to reduce the friction between resin particles, resin melt and processing equipment and between molecules in resin melt, and improve its fluidity and demolding during molding. It is mostly used in the processing and molding process of thermoplastic plastics, including hydrocarbons (such as polyethylene wax, paraffin, etc.), fatty acids, fatty alcohols, fatty acid soaps fatty acid esters and fatty amides, etc. Lubricant is a processing modification additive used in polymer resin to reduce the friction between resin particles, resin melt and processing equipment and between molecules in resin melt, and improve its fluidity and demolding during molding. It is mostly used in the processing and molding process of thermoplastic plastics, including hydrocarbons (such as polyethylene wax, paraffin, etc.), fatty acids, fatty alcohols, fatty acid soaps Fatty acid esters and fatty amides, etc. Silicone oil is the most widely used release agent in industry.
- ⑪ Dispersant. Plastic products are actually a mixture of basic resin and various pigments, fillers and additives. The dispersion of pigments, fillers and additives in the resin is very important to the performance of plastic products. Dispersant is a kind of additive to promote the uniform dispersion of various auxiliary materials in resin. It is mostly used in Masterbatch, colored products and high filling products.
- ⑫ Crosslinking agent. There is not much difference between the crosslinking of plastics and the vulcanization of rubber, but the use of crosslinking additives is not exactly the same. The crosslinking methods of resin mainly include radiation crosslinking and chemical crosslinking. Organic peroxide is the most widely used crosslinking agent in industry. Sometimes, in order to improve the degree and speed of crosslinking, some crosslinking AIDS and crosslinking accelerators are often needed and used. Co crosslinking agent is used to inhibit the free radical breaking reaction of organic peroxide crosslinking agent on the main chain of polymer resin in the crosslinking process, improve the crosslinking effect and improve the performance of crosslinked products. Its role is to stabilize polymer free radicals. The main function of crosslinking accelerator is to accelerate the crosslinking speed and shorten the crosslinking time.
- ⑬ Foaming agent. The auxiliary agent used in polymer coordination system to obtain polymer products with microporous structure by releasing gas and reduce the apparent density of products is called foaming agent. According to the different ways of producing gas in the foaming process, foaming agents can

be divided into physical foaming agents and chemical foaming agents. Physical foaming agents generally release gas depending on the change of their physical state. Chemical foaming agent is based on the gas released by chemical decomposition. According to different structures, it is divided into inorganic chemical foaming agent and organic chemical foaming agent.

- ⑭ Fungicide. Mildew inhibitor, also known as microbial inhibitor, is a kind of stabilizing agent that inhibits the growth of microorganisms such as mold and prevents polymer resin from being eroded and degraded by microorganisms. Most polymer materials are not sensitive to mold, but their products have mold sensitivity because of the addition of plasticizers, lubricants, fatty acid soaps and other substances that can breed mold.
- ⑮ Coupling agent. Coupling agent is a surface modifier of inorganic and natural filling and reinforcing materials. Because most of the reinforcing and filling materials in the plastic industry are inorganic materials and have a large amount of coordination, the processing and application properties of plastic complexes are often reduced when they are directly combined with organic resin. As a surface modifier, coupling agent can organicize the surface of inorganic materials through chemical or physical action, so as to increase the coordination amount and improve the processing and application properties of complexes.

(7) Application of injection molding materials

In terms of development trend, the raw materials of injection molding will still be dominated by oil for a long time in the future. In the past, the research on polymers focused on the exploration of new varieties, new synthetic routes of monomers and new polymerization technologies. At present, with the goal of energy saving, high-efficiency catalysts are used to develop new processes. At the same time, considering the engineering factors in the production process, the work is focused on strengthening the production process (large-scale device, high-speed and continuous process), thin and light products, and the innovation of forming processing technology. Using the existing raw material monomers or polymers, a series of high-performance products with different characteristics can be prepared by compounding or blending (see polymer blends and polymer composites). In recent years, the development and research in this field are increasing, and new composite or blend products are emerging. In terms of functional materials, the application and research work is very active, especially in separation films, photosensitive materials, optical fibers, color changing materials (photochromic, electrochromic, thermochromic, etc.), liquid crystals, superconductive materials, photoconductive materials, piezoelectric materials, thermoelectric materials, magnets, medical materials, medicine and biomimetic materials.

- ① Automotive materials. Because of its light weight, excellent performance, corrosion resistance and easy forming and processing, the application proportion of plastics in automotive materials is increasing. The extensive application of plastic parts significantly reduces the self-weight of the vehicle, reduces fuel consumption, reduces environmental pollution, and improves the beauty and

design flexibility of the vehicle. Nowadays, automobile plasticization is one of the important symbols of the technical level of a country's automobile industry. The application of plastics in automobile includes bumper, fender, trim, radiator mask, oil pipe, fuel tank and instrument panel. There are three main types of plastic parts for automobile: interior parts, exterior parts and other structural functional parts. Plastic manufacturers are also trying to use more plastic to make car floors, windows, steering shafts, springs, wheels, bearings and other functional parts. Automotive plastics include polyethylene, polypropylene, ABS, polyamide, polycarbonate, polyoxymethylene, polyphenylene ether, polymethylmethacrylate, polyvinyl chloride, SAN and polyurethane, their modified materials and composites are generally used.

- ② Magnetic material. Magnetic plastic can record sound, light, electricity and other information, and has the function of playback. It is one of the important basic materials for modern scientific research. Because of its dual functions of plastic and magnetic materials, it has been widely used in many fields, such as electrical, instrument, communication, toys, sports and common products. The traditional manufacturing processes of magnetic materials are casting and powder metallurgy, which have the disadvantages of low production efficiency and high production cost. While injection molding is a new molding process of magnetic plastics, it can overcome the above shortcomings brought by the traditional manufacturing process. In the research of magnetic plastic injection molding, the molding of anisotropic magnetic materials is an important research and application field.
- ③ Medical plastics. Medical plastics is an important field of biomedical engineering industry. It is an emerging industry with the development of modern medicine. Medical plastic products have the characteristics of high technical content and high added value, and their development has great potential. Medical plastics are mainly organic materials. It is a synthetic material with certain biocompatibility. The most commonly used materials for medical plastic products are rubber, polyurethane and its block copolymer, polyethylene terephthalate, nylon, polyacrylonitrile, polyolefin, polycarbonate, polyether, polysulfone, polyvinyl chloride, polyacrylate, etc.
- ④ Plastic optical fiber. Plastic optical fiber (POF) is a soft data transmission medium with low cost, light weight, easy installation and use. It is especially suitable for systems with short distance, small and medium capacity and many connectors. The commonly used plastic optical fiber is PMMA based POF.

5.1.2 Melt Characteristics of Materials

(1) Rheological properties [1, 2]

The rheological properties of materials mainly determine the quantitative relationship between polymer viscosity and melt pressure, temperature and shear rate. It characterizes the basic flow properties of plastic melt and is a very important parameter in injection molding analysis.

- ① Rheological model. The vast majority of plastic melts belong to non-Newtonian fluids. Its main feature is that the shear viscosity decreases with the increase of shear rate, showing the rheological characteristics of “shear thinning”. Although there is no rheological formula to accurately reflect the essence of non-Newtonian plastic melt, it can be characterized by some processing models including processing conditions. Here are two representative machining models:

a. Power law model

$$\eta_{\alpha} = K\dot{\gamma}^{n-1} (n < 1) \quad (5.1)$$

where

η_{α} Apparent viscosity, Pa s;

K Plastic melt consistency;

$\dot{\gamma}$ Shear rate, s^{-1} ;

n Newton exponent.

b. Cross-Arrhenius model or Cross-WLF model

The mathematical model of viscosity is as follows:

$$\eta = \frac{\eta_0(T, P)}{1 + \left(\eta_0 \frac{\dot{\gamma}}{\tau^*}\right)^{1-n}} \quad (5.2)$$

where τ^* is the material constant; η_0 is zero shear viscosity, which is generally expressed by Arrhenius type expression (5.3) or WLF type expression (5.4).

$$\eta_0(T, P) = B e^{T_b/T} e^{\beta P} \quad (5.3)$$

$$\eta_0 = D_1 \exp \frac{-A_1[T - D_2 + D_3 P]}{A_2 + T - D_2} \quad (5.4)$$

Equations (5.2) and (5.3) constitute five parameters (n, τ^*, B, T_b, β) viscosity model, Eqs. (5.2) and (5.4) constitute seven parameters ($n, \tau^*, D_1, D_2, D_3, A_1, A_2$) viscosity model.

② Effect of vibration on rheological properties [3, 4]

In recent years, as a new polymer molding method, vibration molding technology has been studied deeply and carefully by scholars at home and abroad, and many

gratifying results have been achieved. The introduction of vibration field can change the rheological properties of polymers.

The vibration field has an effect on the apparent viscosity, shear stress and shear rate of polymer melt. The effect of vibration field on polymer melt flow performance is related to temperature and pressure. According to the theory of polymer entanglement, the polymer chain in the polymer adopts the conformation of random coil, and the molecular coil is randomly entangled. In the polymer melt, the entanglement between polymer chains occurs and disappears continuously. The “entanglement” and “unwrapping” between molecular chains are a pair of contradictions, which are in a dynamic thermal equilibrium state under certain conditions. In the vibration field, the effect of polymer melt vibration is conducive to hinder the formation of entanglement and enhance the ability of unwrapping. This effect of vibration is shown by the rheological properties of polymer melt, that is, the apparent viscosity decreases and the flow performance increases. Of course, the decrease of polymer melt viscosity is not infinite. When the viscosity decreases to a certain extent with the increase of frequency, the decline rate becomes slow, forming a flat area of the viscosity frequency curve, as shown in Fig. 5.1. The effect of vibration on polymer melt varies with temperature and pressure. When the temperature is low, the viscosity of polymer melt is large, and the apparent viscosity decreases greatly with the increase of vibration frequency. At higher temperature, the decrease of apparent viscosity with the increase of vibration frequency is smaller. The effect of vibration on polymer viscosity is different under different average pressure conditions, as shown in Fig. 5.2. Because the intensity of vibration is related to the frequency and amplitude of vibration, the frequency and amplitude of vibration have an effect on the apparent viscosity of polymer melt. The influence of vibration on the rheology of polymer melt depends on the polymer material. For example, the influence of vibration on the rheology of PS melt is greater than that of HDPE melt.

Fig. 5.1 PS Relationship between apparent melt viscosity and vibration frequency

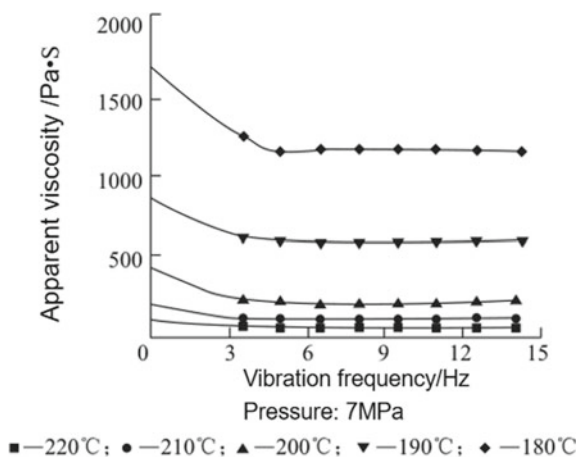
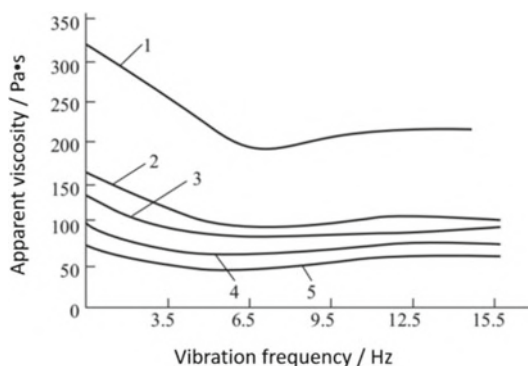


Fig. 5.2 Relationship between apparent viscosity and vibration frequency of PS melt under different pressures



1—7MPa; 2—8MPa; 3—9MPa; 4—10MPa; 5—11MPa

③ Application of rheological properties in injection molding

- a. Use the flow curve to guide injection molding. From the relationship curve $\mu-\dot{\gamma}$ it can be seen that although the viscosity is dependent on the shear rate, the gradient of viscosity change is different in the low shear rate region and the high shear rate region. The small change of shear rate can cause great viscosity fluctuation, which will make injection difficult, cause the instability of injection process, make the mold filling material flow unstable, uneven density, high internal stress and asymmetric linear shrinkage. Therefore, when processing injection molded products, according to the flow curve, the shear rate zone with little effect on viscosity should be selected, which is powerful for stabilizing the processing conditions. Therefore, it is necessary to set the appropriate injection speed on the injection molding machine and select the appropriate gate to realize the mold filling process.
- b. Using the principle of “shear thinning” to guide the injection molding process. Low temperature mold filling is beneficial to improve product quality and reduce molding cycle, so low temperature mold filling is advocated in injection molding process in recent years. Low temperature mold filling is realized by increasing the shear rate, reducing the temperature and maintaining the viscosity. For example, for a polypropylene injection molded product requiring mold filling at a viscosity of 0.0488 Pa s, the following analysis can be made: when the shear rate is 10^2 s^{-1} , the melt temperature needs to be heated to 245.8 °C, but if the shear rate increases to 10^3 s^{-1} , it only needs to be heated to 204 °C. If the latter process scheme is adopted, the melt temperature can be reduced by 41.8 °C, which not only shortens the cooling cycle, improves productivity, but also reduces energy consumption. The method of increasing the shear rate can be realized by increasing the injection speed or by changing the gate section size.

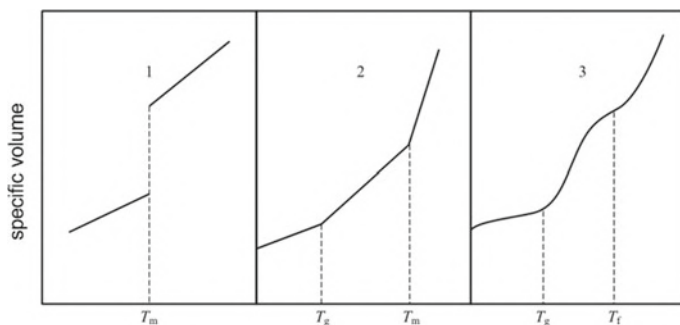
- ④ Application of rheological properties in CAE. CAE technology is computer aided engineering technology. Its emergence is the result of the development of computer aided design/computer aided manufacturing (CAD/CAM) technology in depth. The computer aided engineering technology of injection mold enables the mold to visually and intuitively simulate the actual molding process on the computer screen before manufacturing, predict the impact of mold design and molding conditions on products, find possible defects, and provide a scientific basis for judging whether the mold design and molding conditions are reasonable. However, a large number of data are often used in the injection molding simulation analysis of thermoplastic materials, such as the physical properties of plastic materials (rheological properties/melt viscosity), mold materials and cooling medium materials, as well as the specific process conditions and control parameters of the calculation process. However, injection molding is a very complex physical process. Under the action of pressure, the non-Newtonian high-temperature plastic melt fills the mold cavity with lower temperature through the gate and runner, which has experienced different pressure, temperature and shear rate changes. In order to fully describe the influence of processing conditions on the melt flow properties, it is necessary to know the viscosity of the melt under various conditions (pressure, temperature and shear rate). Although the viscosity under certain conditions can be measured experimentally, it can not be measured under all conditions. The solution is to establish a viscosity mathematical model that can describe the rheological properties of materials under general conditions. Once this kind of model is established, based on the limited experimental values, a certain fitting method can be used to determine the model parameters, so as to calculate the viscosity under complex conditions with considerable accuracy and apply it to other conditions.

(2) Temperature characteristic [5, 6]

In the process of injection molding, after the mold and products are determined, the selection and adjustment of injection molding process parameters will have a direct impact on the quality of products. Among these process conditions, the most important are temperature, pressure and speed, especially melt temperature, which is one of the most important processing variables. It directly affects the properties of the melt, such as viscosity, density and degradation degree. Moreover, melt temperature also determines other processing variables, such as melt flow rate, nozzle pressure, cavity pressure, establishment of cavity pressure during mold filling, mold filling time, cooling process (including injection cycle, production efficiency, shrinkage deformation, etc.). Melt temperature also seriously affects the quality characteristics of injection molded parts, such as weight, density, size and other physical properties and morphology.

① Melting limit and melting point

The process by which a substance changes from a crystalline state to a liquid state is called melting. The melting of polymer crystal is essentially the same as that of low molecular crystal, which belongs to the first-order phase transition process



1-low molecular materials; 2-crystalline polymer; 3-amorphous polymer

Fig. 5.3 Relationship between specific volume and temperature

of thermodynamics. However, the melting process of the two is different. The melting temperature range of low molecular crystal is very narrow, only about 0.2 K. In the whole process, the temperature of the system remains basically unchanged. However, polymer crystals are heated while melting. The whole melting process takes place in a wide temperature range, which is called melting limit. The temperature at which all crystals melt is defined as the melting point (T_m) of the polymer. For amorphous polymers, softening begins when the glass transition temperature is reached, but when the liquid phase changes from high elastic state to viscous flow state, there is no obvious melting point, but there is a melting temperature range T_f for the transition to viscous flow state, as shown in Fig. 5.3.

The commonly used methods for measuring melting point are polarizing microscope, volume expansion method and thermal analysis method.

② Glass transition temperature

The glass transition temperature (T_g) of polymer refers to the transition temperature of linear amorphous polymer from glass state (hard brittle state) to high elastic state (elastic state) or from the latter to the former. From the molecular point of view, with the increase of temperature, the molecular thermal motion energy increases. Although the whole molecule can not move, the motion of the chain segment is excited and the polymer reaches the glass transition region. The deformation of the polymer in this zone increases, and other properties such as specific volume, expansion coefficient, modulus, refractive index, etc. also change abruptly. The glass transition temperature of different varieties of polymers is different. Even for the same polymer, because the chain segment length is a statistical average and the environment of different chain segments is different, the glass transition temperature of materials is often not an accurate temperature point, but a fluctuating temperature range. Generally, the T_g of plastics is higher than room temperature, so plastics are in brittle glass state at room temperature. The glass transition process of polymer is a volume relaxation process. When the polymer changes from high elastic state to glass state, with the decrease of

temperature, the free volume decreases, the adjusted conformation of molecular chain tends to close stack, and the macro performance is that the polymer volume gradually shrinks. After a long time, its volume can reach the equilibrium volume corresponding to a certain temperature, which is the phenomenon of volume relaxation. This phenomenon is closely related to the cooling (heating) speed during the glass transition of polymers, as shown in Fig. 5.4. If the cooling speed is fast, the viscosity of the system increases rapidly, and the chain segments are prematurely frozen in the free volume that has not yet escaped, so the volume has an inflection point at high specific volume, and T_g is high. On the contrary, the cooling speed is too slow, the free volume escape is large, the molecular chains are closely packed, the curve has an inflection point at low specific volume, and T_g is low. If the cooling rate is too fast, not only is there a large residual stress in the product, but there is also a large amount of free volume that escapes during storage, resulting in deformation of the product.

(3) Physical property

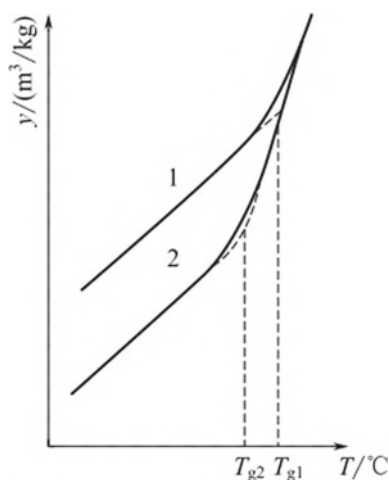
- ① Thermal conductivity. Fourier's law is the basic law of heat conduction, which means that the heat flow is directly proportional to the temperature gradient and the cross-sectional area perpendicular to the heat flow direction, that is:

$$Q = -\lambda A \frac{dT}{dx} \quad (5.5)$$

where

Q conducted heat flow, i.e. heat conducted in unit time, W;

Fig. 5.4 Temperature specific volume curve of amorphous polymer



1 - rapid cooling; 2 - slow cooling

- A heat conduction area, i.e. cross-sectional area perpendicular to the heat flow direction, m^2 ;
- $\frac{dT}{dx}$ temperature gradient, K/m ;
- λ Thermal conductivity refers to the heat transferred through 1 m^2 area within 1 h for a 1m thick material with a temperature difference of $1^\circ (\text{K}, ^\circ\text{C})$ on both sides under stable heat transfer conditions, and the unit is $\text{W}/(\text{m K})$. Thermal conductivity reflects the speed of heat transfer in materials. The higher the thermal conductivity, the faster the heat transfer in the material. The thermal conductivity is related to the composition, structure, density, moisture content, temperature and other factors of the material.

The thermal conductivity of the polymer is very small, so it takes a certain time whether the material is heated in the barrel or cooled in the mold. Generally, the material with low thermal conductivity is called thermal insulation material, and the material with thermal conductivity below $0.05\text{ W}/(\text{m K})$ is called high-efficiency thermal insulation material. Figure 5.5 shows the thermal conductivity temperature curve of low density polyethylene (sample B, see Table 5.1). The thermal conductivity of materials is affected by the loose state of materials (see Fig. 5.6), density and crystallinity (see Fig. 5.7) and thermal history (see Fig. 5.8). In addition, definition

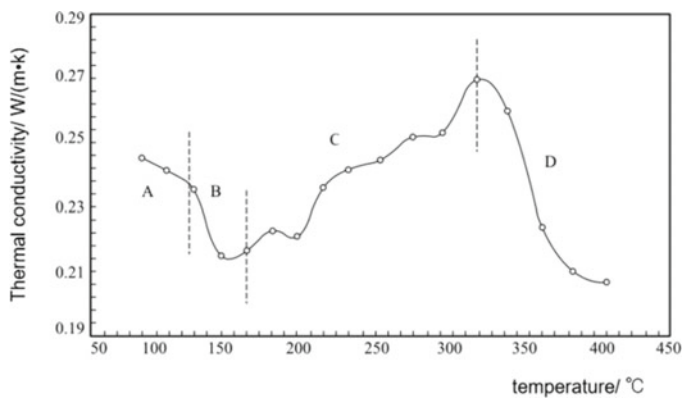


Fig. 5.5 Thermal conductivity temperature curve of low density polyethylene

Table 5.1 Relevant data of samples in Figs. 5.5 and 5.7

Sample name	Crystallization time at 110 °C/ min	Density at 23 °C (g/cm ³)	Crystallinity/%
A	0	0.911	34.0
B	120	0.918	42.0
C	240	0.925	44.0
D	360	0.929	46.9

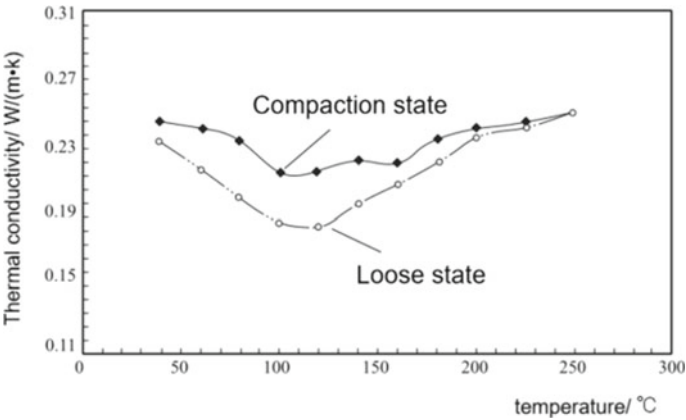


Fig. 5.6 Effect of material state on LDPE thermal conductivity

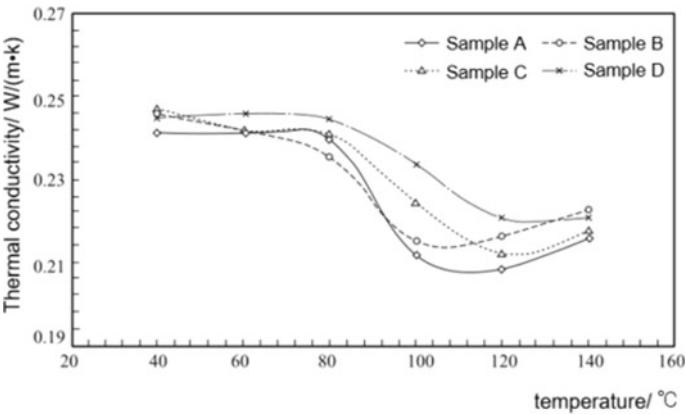


Fig. 5.7 Effect of density and crystallinity on thermal conductivity of LDPE

$$\alpha = \frac{\lambda}{C_P \rho} \tag{5.6}$$

where

- α Thermal conductivity, cm^2/h ;
- λ Thermal conductivity, $\text{W}/(\text{m K})$;
- C_P Constant pressure specific heat capacity, $\text{J}/(\text{kg K})$;
- ρ Density, kg/m^3 .

The thermal conductivity coefficient, also known as the thermal diffusion coefficient, indicates the ability of the internal temperature of the material to be

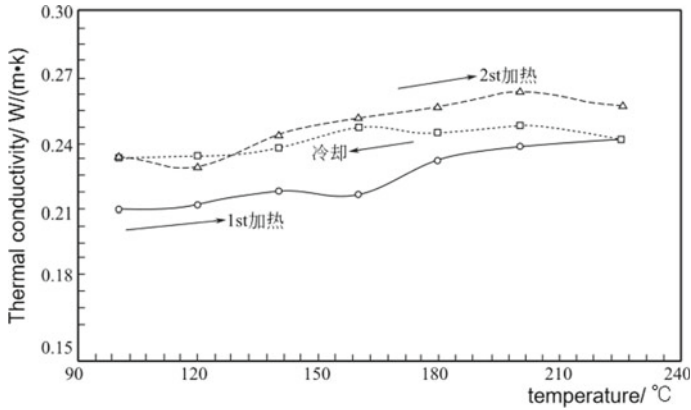


Fig. 5.8 Effect of heating and cooling on thermal conductivity of LDPE

consistent during heating or cooling. The larger the thermal conductivity coefficient, the smaller the temperature difference inside the material; On the contrary, the greater the temperature difference inside the material.

- ② Coefficient of thermal expansion. The change of specific volume with the change of temperature under the condition of constant pressure is the coefficient of thermal expansion. Thermal expansion coefficient can be divided into volumetric thermal expansion coefficient and linear thermal expansion coefficient.
- a. Coefficient of volumetric thermal expansion β , Volume expansion coefficient for short:

$$\beta = \frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_p = \frac{V_T - V_0}{V_0(T - T_0)} = \frac{\Delta V}{V_0 \Delta T} \quad (5.7)$$

- b. Coefficient of linear thermal expansion α , Linear expansion coefficient for short:

$$\alpha = \frac{1}{L} \left(\frac{\partial L}{\partial T} \right)_p = \frac{L_T - L_0}{L_0(T - T_0)} = \frac{\Delta L}{L_0 \Delta T} \quad (5.8)$$

where

V_0 specific volume at initial temperature T_0 ;

V_T specific volume at termination temperature T ;

L_0 length at initial temperature T_0 ;

L_T length at termination temperature T .

For isotropic solids, the volume expansion coefficient is 3 times of the linear expansion coefficient. Among solids, liquids and gases, the volume expansion coefficient of gas is the largest and that of solid is the smallest.

(4) PVT characteristic [7]

Pressure volume temperature (PVT) of polymers and their blends, as the basic properties of polymers, plays a very important role in the production, processing and application of polymers. Based on PVT data, many thermodynamic quantities and equation of state (EOS) parameters can be obtained by thermodynamic calculation method, and then the phase separation behavior and blending compatibility of polymers and their blends can be studied, so as to guide the processing and preparation of polymers.

5.1.3 Processing Properties of Materials

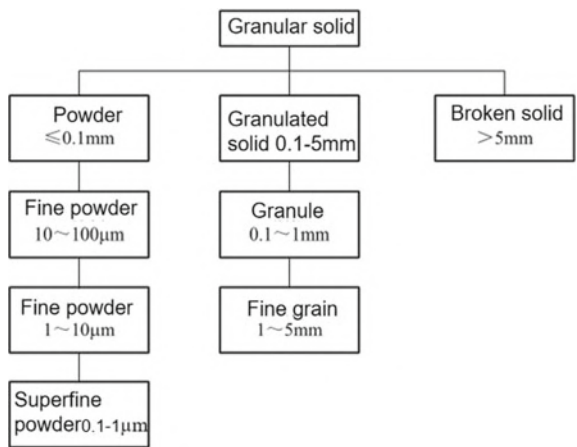
(1) Plasticizing properties

During the injection process, the plastic experienced a transition from solid state to semi molten state to molten state. The transport performance of solid materials has a great influence on the plasticization characteristics of molding processing. The important parameters are the size and shape of solid particles, bulk density and friction coefficient.

- ① Size and shape of solid particles. Polymer particles for injection molding range from 1 to 1 mm. Figure 5.9 shows the terms commonly used to describe granular solids in a certain particle size range.

The shapes of particles are mainly arbitrary, angular, cylindrical and spherical. The transport characteristics of granular solids are very sensitive to the

Fig. 5.9 Terminology of granular materials



shape of particles. Even if the particle size remains unchanged, the internal and external friction coefficients can essentially change with the change of particle shape. Small differences in the granulation process will cause fluctuations in the plasticization process.

The ease of solids transfer is often determined by the particle size. Granular materials are usually free-flowing and do not trap air. Fine granules are either free-flowing or semi-free-flowing and may contain air. Semi-free-flowing fines require special feeding devices to ensure stable plasticisation. Powders are prone to coalescence and air entrapment and the difficulty of plasticising them increases with decreasing particle size. Crushed solids are often irregular in shape and generally have a low bulk density, making them more difficult to feed.

- ② Bulk density. The bulk density of the loose material formed by solid particles refers to the density obtained by dividing the mass of the material by the volume when the loose material is loaded into a container of a certain volume without pressure or tap.

The compressibility of loose materials largely determines the solid transportation behavior. The compressibility of polymer pellets can be expressed as:

$$\text{Compressibility} = (\text{bulk density of loose material} - \text{bulk density of compacted material}) / \text{bulk density of loose material} \quad (5.9)$$

When the compressibility is less than 20%, the polymer particles are free flowing materials; When the compression ratio is higher than 20%, the polymer pellets are non free flowing materials; When the compression rate is higher than 40%, the material has a very strong compression tendency in the feed hopper, and it may be difficult to feed at this time.

Stack the materials into piles, and the side of the conical material pile forms an included angle with the horizontal plane, which is called the angle of repose, as shown in Fig. 5.10. The research shows that the angle of repose of 45° can roughly be used as the boundary between free flow materials and non free flow materials. The angle of repose of non free flow materials is greater than 45° and that of free flow materials is less than 45° .

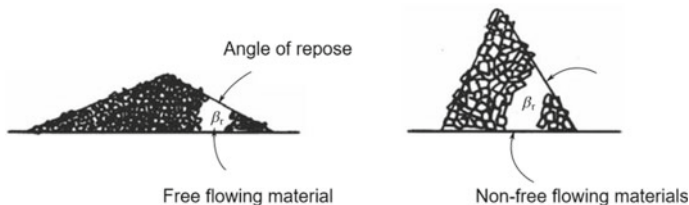


Fig. 5.10 Resting angle

Table 5.2 Relationship between material shape and density, angle of repose and plasticization (LDPE)

Shape	Density/(g/cm ³)	Angle of repose/(°)	Plasticizing amount/(kg/h)
Arbitrary shape	0.29–0.30	42.5	22.7
Angular shape	0.40–0.48	40	41.3
Cylindrical	0.50–0.50	32.5	43.1
Spherical	0.54	22	45.4

The relationship between material shape and density, angle of repose and plasticization is shown in Table 5.2.

It is only a very rough index to take the compressibility and angle of repose as the judgment basis of free flow and non-free flow. In fact, the compaction of polymer pellets is a very complex process, which is affected by many factors. In the process of compaction, the distribution of material stress is complex, and many depend on the geometry and surface condition of the hopper and the characteristics of loose materials.

- ③ Friction factor. The friction coefficient of loose materials is another very important performance, which can be divided into internal friction coefficient and external friction coefficient. The internal friction coefficient is a measure of the resistance generated when a particle layer of the same material slides over another particle layer. The external friction coefficient is a measure of the resistance at the wall interface between polymer particles and different structural materials.

There are many factors affecting the friction variables. Temperature, sliding speed, contact pressure, metal surface state, polymer particle size, compaction degree, time, relative humidity and polymer hardness will all affect the friction coefficient. For example, the coefficient of friction is very sensitive to the state of the metal surface. The friction coefficient of a polymer pellet on a completely clean metal surface is very low, below 0.05. However, when the polymer slides on the surface for some time, the friction coefficient will increase significantly. The relationship between partial plastic friction coefficient and temperature measured by the device shown in Fig. 5.11, as shown in Fig. 5.12. Test conditions: the friction speed is 87 mm/s and the pressure is 0.53 MPa. As can be seen from Fig. 5.12, there are great differences among various materials.

Bartenev and Lavrenl simulated the friction process in the screw, measured the friction properties of various polymers, and listed the relationships between temperature, sliding speed, normal stress and friction coefficient. For example, as shown in Fig. 5.13, the material is polyethylene, the sliding speed is 0.6 m/s, and the relationship between external friction coefficient and temperature under different pressures. Under low pressure, the friction coefficient increases with the increase of temperature, it peaked at the melting point and then began to decline rapidly. Under high pressure, the friction coefficient decreases monotonically with the increase of temperature.

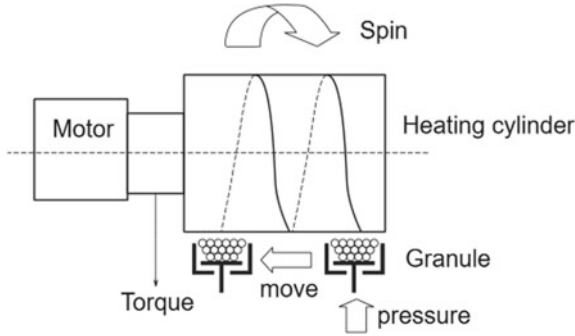


Fig. 5.11 Measuring device for friction coefficient between plastic and metal surface

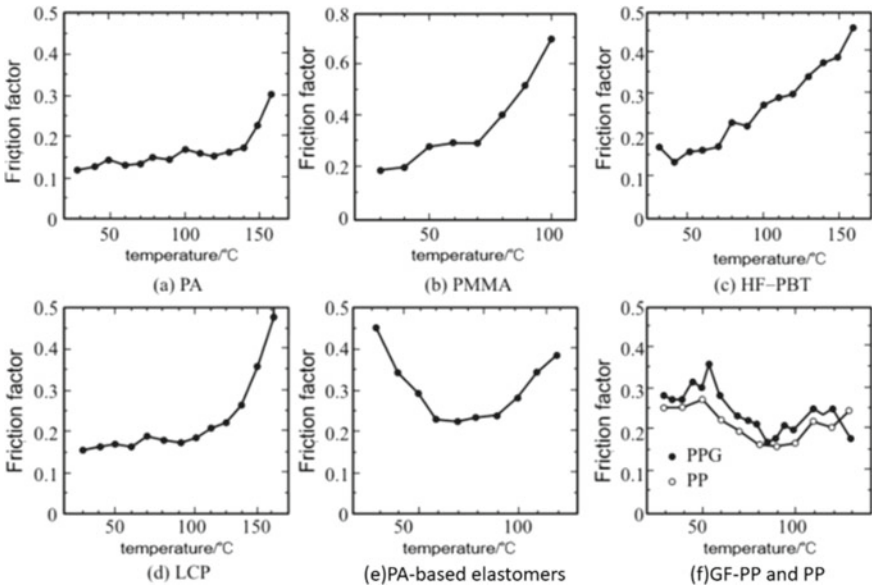


Fig. 5.12 Relationship between friction coefficient and temperature

The fluidity of granular materials is determined by their shear properties. The local shear stress immediately after internal shear deformation is called shear strength. Shear strength is a function of normal stress. The shear performance of particle solids can be measured by the shear dish developed by Jenike, as shown in Fig. 5.14. The friction coefficients of polymer with barrel and screw are respectively μ_c and μ_s . The necessary conditions for normal processing are:

$$F_c > F_s, \text{ i.e., } \mu_c S_c > \mu_s S_s$$

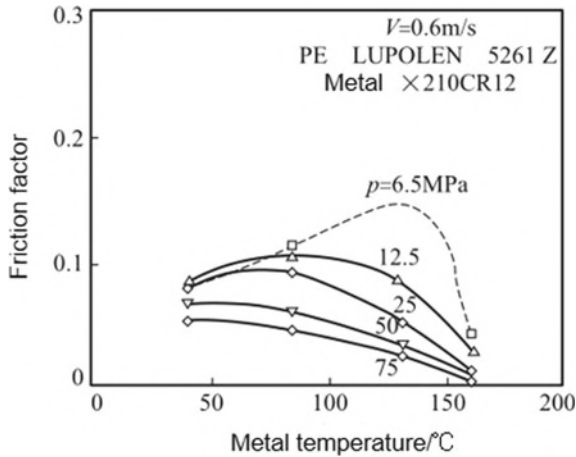
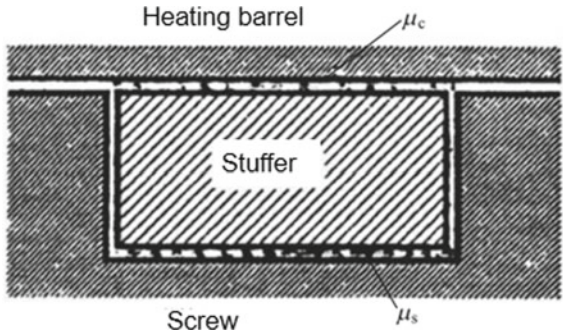


Fig. 5.13 Relationship between external friction coefficient and temperature



$\mu_s > \mu_c$: The material barrel is attached to the screw and does not rotate forward; $\mu_s < \mu_c$: The plug is conveyed forward.

Fig. 5.14 Schematic diagram of material and friction coefficient

(2) Thermal stability [8–11]

Thermal stability refers to the maximum residence time that a polymer can withstand at processing temperature. As shown in Fig. 5.15, the relationship between POM residence time and melt temperature, and the curve in the figure is the residence time limit. If the residence time of POM at a certain temperature exceeds the limit value, the material will decompose. Figure 5.16 shows the adverse effects of thermal decomposition.

① Causes of thermal decomposition

- a. Molecular weight decreased. Plastics are composed of macromolecular chains, which are not uniform. The molecular weight of plastics refers to its

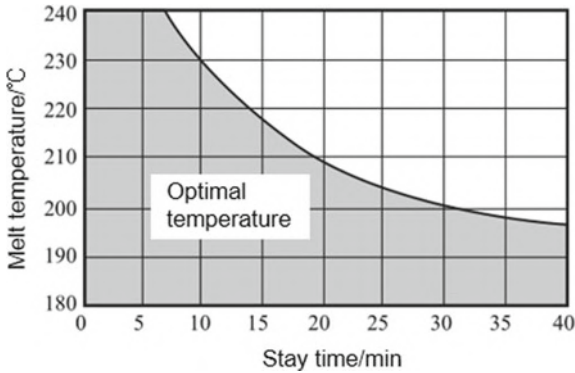


Fig. 5.15 Recommended maximum residence time for POM injection molding

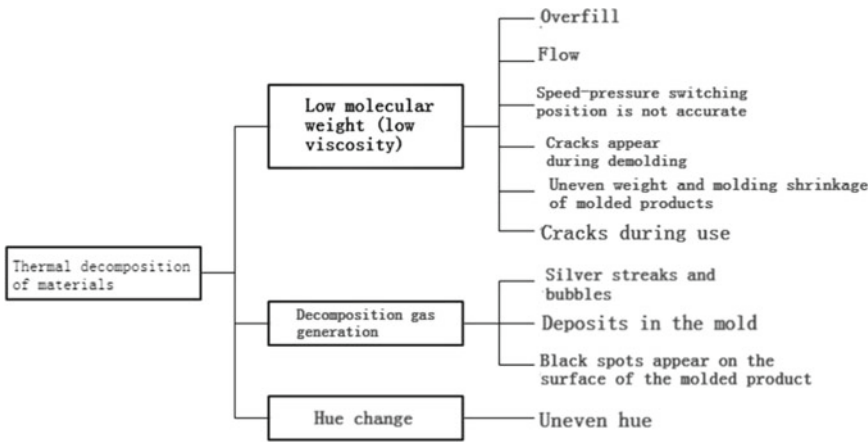


Fig. 5.16 Adverse effects of thermal decomposition and molding of materials

average value. The average molecular weight and molecular weight distribution have a great impact on the properties of materials. With the increase of molecular weight, the viscosity of the material also increases. When the temperature increases, the thermal energy will cause the fracture of molecular chain, resulting in the decrease of molecular weight and melt viscosity. When the molecular weight decreases, the physical properties of the material will also change, for example, the impact strength decreases (the material becomes “brittle”).

- b. Oxidation. Similarly, for POM, at the processing temperature (more than 160 °C, from solid state to molten state), POM is oxidized in contact with air, and the molecular chain is broken. This phenomenon can be observed if the plasticizing device adopts exhaust structure. The length diameter ratio of the screw in the exhaust plasticizing device is large (more than 32), and the

- residence time of the melt in the barrel is prolonged, which will also lead to decomposition. Therefore, for some raw materials, the exhaust structure should be carefully selected to prevent oxidation reaction.
- c. Hydrolysis. With the participation of water, some materials decompose faster than pure heat. When the water content of the composite exceeds 0.05%, hydrolysis will occur and the processed products will be brittle. Therefore, before processing, materials with strong water absorption and easy hydrolysis should be dried, especially for recycled materials.
 - d. Additive decomposition. Due to the limitations of the performance of a single resin, in order to meet the requirements of comprehensive performance, it is inevitable to compound a variety of resins or resins with a variety of additives. There are many kinds of additives, and the following additives are prone to thermal decomposition: low molecular polymers, residues during resin synthesis, fillers, surface treatment agents, etc. To overcome such defects, additives should be reasonably selected according to processing conditions.
- ② Evaluation of thermal stability. The commonly used methods are analytical method and injection molding method.
- a. Analytical method. There are generally thermogravimetric analysis and differential scanning calorimetry.
- Thermogravimetric analysis (TG, TGA) is a function of observing the change of sample quality with temperature or time during heating, constant temperature or cooling. Figure 5.17 shows the thermogravimetric analysis results of PC. It can be seen from the figure that the weight of the sample begins to decrease at 525 °C, that is, it begins to decompose. At 560 °C, the weight will not decrease, and the decomposition is over.
- Differential scanning calorimetry (DSC) is to make the sample at the programmed temperature and observe the heat flow difference between the sample and the reference as a function of temperature or time. Figure 5.18

Fig. 5.17
Thermogravimetric analysis
curve of PC

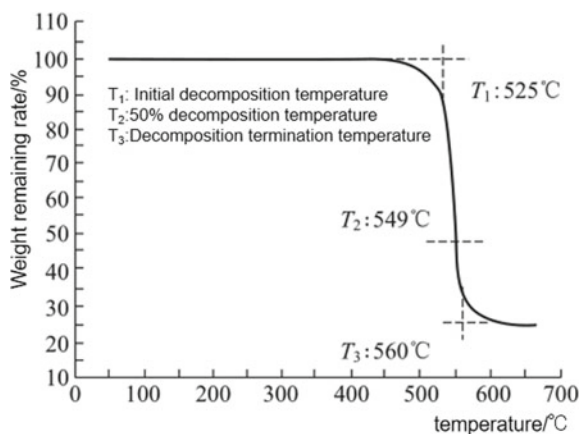
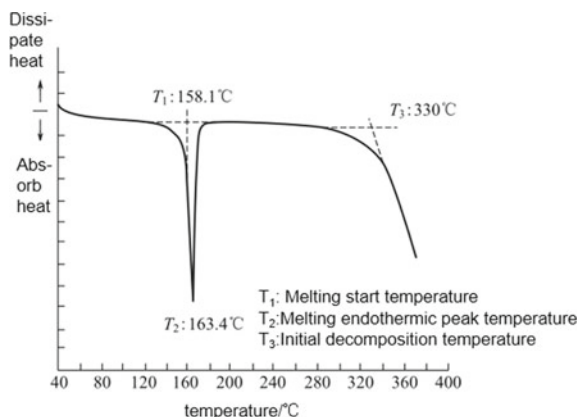


Fig. 5.18 DSC analysis curve of POM



shows the DSC analysis curve of POM. It can be seen from the figure that at 163.4 °C, the material begins to absorb heat, indicating that the material begins to melt, and the endothermic phenomenon occurs again at 330 °C, which is the beginning of decomposition.

- b. Injection molding. This method uses an injection molding machine to obtain the curve between residence time and molding temperature through experiments, and sets the processing temperature according to the curve. Taking polypropylene processing as an example, the first set injection temperature is 260 °C (subject to the barrel heating temperature), the injection time is 5 s, the cooling time is 10 s, the mold temperature is 60 °C, the initial injection pressure is 70 MPa, forming three times continuously under this process condition, then pressurizing 300 kPa each time, injecting three times each time, recording the time of filling the mold cavity for each injection, and the pressure when it can not only fill the mold cavity quickly but also overflow can be regarded as the maximum limit pressure. At the set initial pressure point, lower the pressure according to the above method, and find the pressure when the material cannot be filled with the mold the minimum limit injection pressure in the same way. Then fix the pressure and temperature under a certain condition that can ensure normal injection, heat up step by step, raise the temperature by 10 °C each time, and form three times, and find the temperature that can not be normally shaped and cooled due to too high temperature and can not form intact products—the maximum injection temperature. Then return to the initial set temperature, reduce the temperature by 10 °C each time and form three times until the product has various defects or cannot be injected normally. At this time, the temperature is the minimum

injection temperature. In the same way, the minimum injection molding cycle is determined under the condition of fixed injection temperature and pressure.

(3) Mobility

The molecular weight, viscosity, volatile content, moisture content and melt fluidity of the same plastic are also different due to different origin, specification and brand. These indexes directly affect the injection rate and mold filling. For plastics with different melt fluidity, the best value can be achieved by adjusting injection pressure, injection speed, pressure holding time and injection temperature. Plasticizer and lubricant can be added to the raw materials with poor melt fluidity to improve the fluidity, and finally the best product can be obtained by changing the injection process conditions. However, it should be noted that excessive melt fluidity will lead to nozzle salivation.

The most commonly used parameter to characterize the fluidity of materials is melt flow rate (MFR). The melt flow rate of material is obtained by point measurement with plunger extruder or extrusion speedometer, and its principle is shown in Fig. 5.19. Firstly, the material is added into the barrel for heating, and the standard weight is installed on the piston as the power. The melt is extruded from a short round hole die. The gram of the extruded material within 10 min is the melt flow rate of the material. The larger the melt flow rate, the better the fluidity of the material.

In addition, the fluidity of the material can be evaluated by measuring the flow length of the melt in the mold cavity. Figure 5.20 shows a test mold. A pressure sensor is set in the mold cavity. While testing the melt flow length, it can also monitor the pressure of the melt flowing through some points (for example, points A, B and C in Fig. 5.20).

Fig. 5.19 Working principle of melt flow rate tester

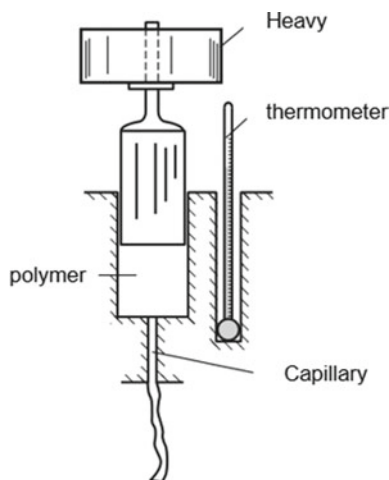
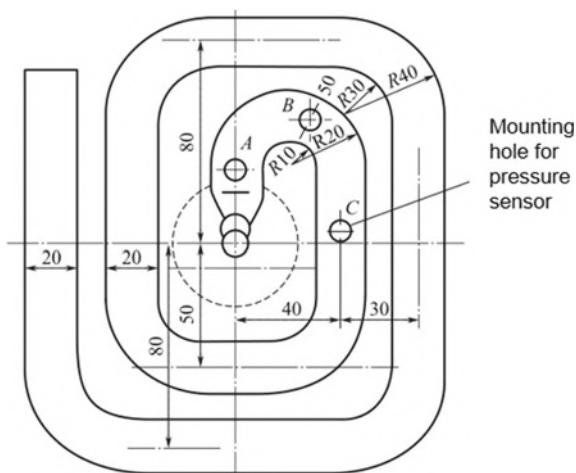


Fig. 5.20 Melt flow length test die



(4) Preparation of materials

In order to make the injection process smooth and ensure the quality of plastic products, some necessary preparations should be carried out before molding, including determining the properties of raw materials, dyeing of raw materials, granulation of powder, preheating and drying of plastics, etc. Due to the different types and forms of injection raw materials, the structure of plastic products, whether there are inserts and use requirements, the preparation before molding of various plastic parts is not exactly the same.

- ① **Raw material performance confirmation.** The performance and quality of plastics will directly affect the quality of plastic products. In recent years, due to the rapid development of plastic industry, new plastic varieties are emerging. It is possible to choose a variety of brands for the same kind of plastics. The properties and quality of the same type of plastics from different producing areas are also different. Plastics containing various additives in different proportions are also emerging one after another, and their process properties are also different. Therefore, before mass production, the properties and quality of the plastics used should be fully confirmed. The main contents include the inspection of raw material appearance (such as color, particle size and uniformity) and the determination of process properties (melt flow rate, MFR, fluidity, thermal properties and shrinkage). The requirements for appearance are uniform color, uniform particle size and no impurities.

MFR is one of the important process properties. MFR is used to determine the fluidity of thermoplastic in the molten state, and can be used to select the processing temperature and pressure of plastic molding. For a plastic raw material, if the MFR is large, it means that its average molecular weight is small and its fluidity is good. Lower temperature and pressure can be selected during

molding, but the average molecular weight is low and the mechanical properties of the product are relatively low; On the contrary, it means that the average molecular weight is large, the fluidity is poor, and the molding process is difficult. The MFR of plastic materials for injection is usually 1–10 g/10 min. For products with simple shape or high strength requirements, choose a smaller MFR value; For products with complex shape, thin wall and long process, a larger value should be selected.

The performance parameters of plastics can generally be obtained from the material supplier. If the required parameters are unknown, they need to be tested according to the corresponding test standards.

- ② Preheating and drying of plastics. In the process of plastic molding, the residual water in plastic raw materials will be gasified into water vapor, which will remain in the interior or surface of the product, forming silver filaments, stripes, bubbles, pits and other defects. Even if the degree is slight, the surface of the product will lose its original luster and appear dim and uneven color, and local dark spots will appear on electroplated parts and painted parts, The presence of water and other volatile low molecular compounds will also play a catalytic role in the high heat and high pressure processing environment, which will crosslink or degrade some sensitive plastics, such as polycarbonate, nylon and some ABS materials, which will not only affect the performance quality, but also seriously reduce the performance. Therefore, before plastic molding and processing, pre drying must be used to remove moisture and other easily gasified substances. This process is called drying. See Table 5.3 for the allowable water vapor and hot air drying process of some commonly used plastics. If this standard is exceeded, the injected products will become inferior due to the action of water vapor.

Plastic drying methods include oven drying, infrared drying, plate drying and high-frequency drying. Plastic drying equipment includes hot air circulation drying oven, static or rotary direct air drying oven, far infrared drying oven, hot air hopper dryer, dehumidification hopper drying unit, boiling dryer, etc. common drying methods of thermoplastic plastics mainly include hot air circulation drying and infrared drying.

- a. Hot air circulation drying. The drying principle is to use hot air to take away moisture and volatiles through the plastic surface. The hot air circulation oven requires that the baked plastic be flattened, and the thickness shall not exceed 2.5 mm. The drying time is usually determined by the moisture content of the plastic and the oven temperature. The drying equipment based on the principle of hot air circulation mainly includes hot air circulation oven, hot air hopper dryer, boiling dryer, etc.

The hot air hopper dryer directly introduces hot air from the bottom of the hopper to dry the plastic. This structure avoids a lot of trouble caused by the operation of the oven, is conducive to realizing the continuity and automation of feeding, and shortens the drying time. The time of drying with it is much shorter than that of the oven, so it is generally necessary to use a higher temperature, but it should be noted that the plastic surface cannot be sticky,

Table 5.3 Allowable water vapor and hot air drying process of some plastics

Types of plastics	Abbreviate symbol	Injection allowable water Steam fraction	Drying temperature/ °C	Time/h
Polyethylene	PE	< 0.1	90–100	< 0.5
Polypropylene	PP	< 0.1	100–120	< 0.5
Polystyrene	PS	0.05–0.1	71–79	1–3
	ABS	< 0.3	< 70	4
Polyvinyl chloride	PVC	< 0.08	60–93	
Polycarbonate	PC	< 0.2	110–120	8
Thermoplastic polyester	PET	< 0.1	80–95	2–12
Polybutyric acid	PBT			
Polyamine	PA	0.4–0.9	80–100	16
Polyether gum	PEI		120–150	2–7
Polyamine imide	PAI		150–180	8–16
Polymethylmethacrylate	PMMA	0.1–0.2	100–120	1
Polyoxymethylene	POM		80–120	
Poly alum	PSU	< 0.05	110–120	3–4
Polyphenylene ether	PPO		110–120	
Ether polyetheretherketone	PEEK		150	
Thermoplastic polyurethane	TPU		100–110	1–2
Thermoplastic elastomer	TPE		120	3–4
Liquid polymer	LCP		110–150	4–8
Poly aryl ester	PAR		120–150	4–8
Polyphenylene sulfide	PPS		140–250	3–6
Poly alum	PES			
Poly aryl alum	PASU		135–180	
Ethylene butyl acrylate copolymer	EBA		70–80	3
Polyether amide block copolymer	PEBA		70–80	2–4
Cellulose acetylbutyrate	CAB		60–80	2–4
Cellulose acetate	CA			
Cellulose propionate	CP			

otherwise it will affect the falling of plastic from the hopper. In addition, for plastics mixed with various additives, it should be considered whether the mixture will be separated under the action of hot air. If it is separated, the hot air hopper dryer cannot be used.

- b. Infrared drying. Infrared drying uses infrared radiation to dry plastics. During infrared heating, the plastic surface is heated first, and then the heat is transmitted to the inside through heat conduction. The thickness of the plastic layer should not exceed 6 mm. Generally, plastic is loaded on a conveyor belt and passed under an infrared lamp. The temperature of drying plastics is related to power, number of lamps, distance between plastics and lamps, heating area of plastics and heating time. Generally, the temperature of radiation source is set between 400 and 600 °C. In the drying process, an air supply device is equipped to take away moisture and volatiles, which is conducive to improving efficiency.

- ③ The coloring process. Most thermoplastic raw materials are transparent or milky white. With the improvement of people's living standards and the improvement of product performance requirements, people often put forward various requirements for product color. Therefore, coloring is required before the processing of plastic products, that is, different components of colorants are mixed in the plastic to make it have specific color or specific optical properties.

The coloring process is not only related to the selected colorants, but also related to the properties of plastics, additives, processing means and application methods. When selecting colorants, they should be selected with reference to the properties of colorants.

There are two common methods for coloring plastic raw materials, namely dry mixing method (also known as floating dyeing method) and color masterbatch coloring method.

- a. Dry mix coloring. Dry mixing coloring is to mix thermoplastic particles, dispersant and pigment evenly into colored particles and then inject them directly. The dispersant for dry mixing coloring is generally white oil, and turpentine, alcohol and some esters can also be used as needed. The specific operation process is as follows: add plastic particles and dispersant in the high-speed kneader, mix and stir, and then add pigment; With the help of the high-speed rotation of the stirring slurry, the particles rub against each other to produce heat; The pigment powder is firmly adhered to the surface of plastic particles by dispersant. The dyeing process of dry mixing method is simple and low cost, but it has certain pollution and needs mixing equipment; If manual mixing is adopted, it will not only increase the labor intensity, but also uneven mixing, affecting the coloring quality.
- b. Color Masterbatch method. Color Masterbatch coloring method is to mix thermoplastic particles and color masterbatch particles in a certain proportion for injection molding. The color masterbatch coloring method has the

advantages of simple and convenient operation, uniform coloring, no pollution and higher cost than the dry mixing method. Recently, the law has been widely used.

- ④ Insert preheating. Before injection molding, the metal insert is first placed in the predetermined position in the mold, and then formed into a whole with the plastic. Because the thermal properties of metal inserts and plastics are very different, resulting in different shrinkage rates, plastic products with inserts are easy to produce cracks around the inserts, which not only affects the surface quality of products, but also reduces the strength of products. The solution to this problem is not only to increase the thickness of plastic around the insert when designing products, but also to preheat the metal insert. The preheating of the insert must be determined according to the nature of the plastic and the type and size of the insert. For plastics with rigid molecular chains (such as PC, PS, polysulfone and polyphenylene ether), because these plastics are easy to crack, when there are inserts in the products, the inserts must be preheated; For plastics with flexible molecular chains (such as PE, PP, etc.) and small inserts, the inserts are easy to be heated in the mold by molten plastics, and the inserts may not be preheated. The preheating temperature of the insert is generally 110–130 °C, and the preheating temperature is limited to not damaging the coating on the surface of the insert. For aluminum alloy or copper inserts without coating on the surface, the preheating temperature can be increased to about 150 °C. The preheating time is usually a few minutes.
- ⑤ Cleaning of barrel. In the process of injection molding, when the original materials need to be replaced, the plastic to be used later or another cleaning material that can be mixed into the barrel to remove the residual old materials in the barrel is called barrel cleaning. In production, when it is necessary to change raw materials, change colors or find plastic decomposition, the barrel of the injection molding machine shall be cleaned. There are two refueling cleaning methods: direct refueling method and indirect refueling method.
 - a. Direct refueling method. If there is a common melting temperature between the raw material to be changed and the remaining material in the barrel, the residual material can be directly replaced with the material to be produced. If the molding temperature of the raw material to be replaced is higher than the temperature of the material left in the barrel, first raise the barrel and nozzle temperature to the minimum processing temperature of the raw material to be replaced, then add the material to be replaced and conduct continuous air injection until the residual material in the barrel is cleaned, and then adjust the temperature for normal production. If the forming temperature of the material to be refueled is lower than the temperature of the remaining material in the barrel, first raise the temperature of the barrel and nozzle to make the remaining material in the best flow state, then cut off the heating power supply of the barrel and nozzle, clean the material to be refueled under cooling, and turn into production when the temperature drops to the processing temperature of the material to be refueled.

- b. Indirect refueling method. If there is no common melting temperature between the raw material to be replaced and the remaining material in the barrel, the indirect refueling method can be used. If the forming temperature of the material to be refueled is high and the remaining materials in the barrel are heat sensitive, such as PVC and POM, in order to prevent plastic degradation, two-step refuelling cleaning shall be adopted, that is, PS or LDPE plastic with good thermal stability or the return of such plastic shall be used as the transition cleaning material for transition refuelling cleaning, and then the transition cleaning material shall be replaced with the material to be refueled. Because direct refueling cleaning wastes a lot of cleaning materials, barrel cleaning agent has been widely used to clean the barrel. The use method of barrel cleaning agent is as follows: firstly, raise the barrel temperature to 10–20 °C higher than the normal production temperature, inject the remaining materials in the barrel, and then add cleaning agent (the dosage is 50–200 g); Finally, add the material to be refueled and inject it into the air continuously for a period of time in the way of pre molding. If one cleaning is not ideal, repeat cleaning.

(5) Demolding property

In the final stage of the injection process, the mold opens and the product leaves the mold. The difficulty of separating the product from the mold is called demolding. The requirement of demolding is that the product can be separated from the cavity or core smoothly, and the whole ejection process will not cause any damage and deformation to the product. The main factors affecting the demolding performance are slope or taper, surface roughness, chamfer and hole, position of parting line, etc. Almost all characteristics related to specific geometry will affect the ejection and demolding characteristics of products. If demolding is not considered in product design, even for very simple products, the ejection and demolding system may be very expensive.

- ① Slope or taper. Slope or taper is usually used to facilitate the ejection of products with large forming depth. If the standard cavity and core are used to produce products, the cavity is connected with the fixed template, and the core is connected with the moving template. The purpose of setting the slope on the side wall of the cavity is to separate the product from the cavity when opening the mold and reduce the scratch or wear on the side surface of the cavity when opening the mold. Setting the cavity slope helps the air flow, so as to eliminate the vacuum effect during mold opening. The typical cavity inclination varies from a few degrees to a few degrees, which is affected by the changes of molding depth, material rigidity, surface lubricity, mold surface roughness and material shrinkage. Once the mold is opened and the product is removed from the cavity, it must be stripped from the core as soon as possible. Plastic products are easy to clamp on the core, so it takes a lot of force to eject the products. The products with zero core inclination are difficult to eject, and there is a high ejection force in the ejection cycle. Therefore, the core is usually inclined, and the inclination range is 0.25°–2°. In

most cases, the core slope is equal to the cavity slope. This parallel structure is better because it keeps the wall thickness of the product uniform.

- ② Surface roughness. The surface roughness of cavity and core has a great influence on the demolding performance of plastic products. The type of die steel or surface coating, surface roughness and polishing direction are very important factors. Generally, the smoother the surface and the higher the degree of polishing are, the more conducive to the demolding of the product. This is especially true of brittle, hard or glassy polymers. In other cases, slight surface texture or sand blasting can also reduce the jacking force, which is applicable to some elastomer or ductile materials. Practice has proved that the polishing direction has a great influence on the ejection of products. The polishing direction of core and cavity should be consistent with the direction of mold opening, especially for products with large molding depth and small or no inclination. For cavities with random texture, according to experience, the texture depth shall be 0.025 mm and the slope of each side shall be 1° – 5° . Because the material shrinks, the texture on the core will hold the product tightly on the core, making it particularly difficult to demold. Therefore, if there must be texture on the core, a large slope is required. In the ejection process, the friction between plastic products and molds can be reduced by using lubricants or changing the surface coating of molds. Lubricants are usually added to plastic materials. Lubricants are generally divided into internal and external use. Internal lubricants are additives with strong affinity with polymers, which can be used to reduce the viscosity of molten polymers. On the contrary, the external lubricant has low solubility in the polymer and tends to migrate from the polymer body to the metal contact surface of the processing equipment during the processing to produce a lubricating surface. The external lubricant is a good method to replace the spraying release agent. It can overcome the problems such as prolonged cycle, inconsistent processing process, inconvenient surface finishing and assembly caused by spraying release agent. Another method to reduce the demolding force is to electroplate materials with low friction coefficient on the mold or carry out surface treatment, such as electroless nickel plating, electrolytic chromium plating, molybdenum disulfide coating, tungsten disulfide coating, amorphous boron carbide coating, five electroplated nickel plating impregnated with polytetrafluoroethylene, etc.

There are three common release agents, namely zinc stearate, white oil and silicone oil. Zinc stearate can be used in general plastics except PA; The effect of white oil as the release agent of PA is better; Although silicone oil has good demolding effect, it is inconvenient to use. It needs to be prepared into toluene solution and coated on the surface of the mold. It can show excellent effect after drying.

There are two methods for the use of release agent: hand coating and spraying. Hand coating method has low cost, but it is difficult to form a uniform film on the mold surface. After demolding, it will affect the apparent quality of products, especially transparent products, and produce surface turbidity. Spraying method is to spray the liquid release agent evenly after atomization, with thin coating, good release effect and many release times (more than ten molds can be removed

at one time). In actual production, spraying method should be selected as far as possible. It should be noted that for plastic products to be electroplated or surface coated, release agent shall not be used as far as possible.

- ③ Chamfers and holes. When designing plastic injection products, some special mold activities should be avoided as far as possible, such as lateral movement, lateral core pulling, inclined core rod folding core and buckle withdrawing mold. These special mold functions make the mold cost expensive, increase the mold maintenance cost, hinder the design of the mold cooling system, and may eventually lead to the extension of the product production cycle. Even if the special mold movement mode must be used, its application should be limited as far as possible. If the lateral movable mold must be used, it is best to make the movement direction perpendicular to the mold opening direction, and oblique movement should be avoided as far as possible.
- ④ Parting line position. Chamfering can be avoided by changing the placement method of the product in the mold. According to the product orientation shown in Fig. 5.21a, it is necessary to install a movable core or return rod to facilitate ejection. If the product is put into the mold at the angle shown in Fig. 5.21b, the product will be easily ejected.

(6) Residual stress characteristics

The formation of residual stress in injection molding is mainly attributed to two factors: cooling and flow stress. The most important is the residual stress formed by rapid cooling or quenching of the product in the mold cavity. Typical residual stress distribution is shown in Fig. 5.22. The experimental results of PMMA and PS sheets cooling under different conditions are shown in Fig. 5.22. (1) 3 mm thick PMMA sheet is cooled from 170 °C or 130 °C to 0 °C, (2) 6 mm thick PS sheet is cooled from 150 °C or 130 °C to 23 °C.

In the filling and pressure maintaining stage, the shear stress and normal stress of polymer melt flow in the mold cavity can also form the residual stress of injection molded products. These flow induced tensile stresses are usually much smaller than those formed during cooling. However, at low temperature injection, these stresses may be very large, and tensile residual stresses are formed on the surface of the product.

In order to improve the mold and simulate and predict the shrinkage and warpage of plastic products in the processing process, it is necessary to control the complex thermodynamic behavior of materials in the processing process. Shrinkage and warpage come from the non-uniformity and anisotropy of materials, which are caused by mold

Fig. 5.21 Changing the orientation of the product in the mold can eliminate the internal chamfer, so as to simplify the ejection of the product

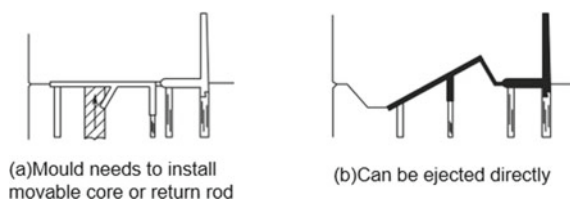
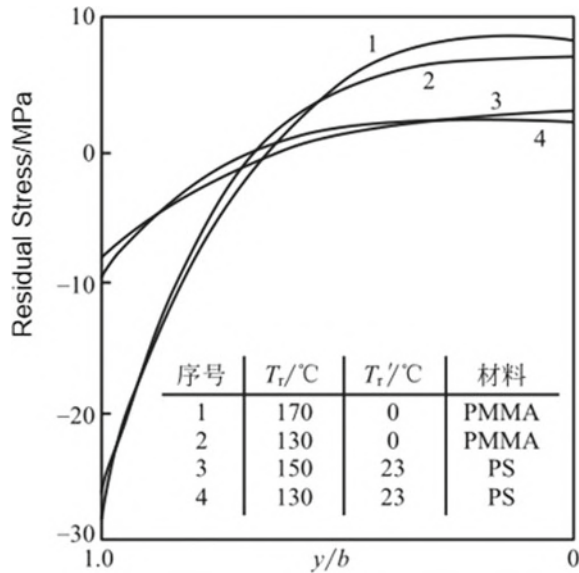


Fig. 5.22 Residual stress distribution



filling, molecular or fiber orientation, crosslinking or curing behavior, inappropriate thermal mold layout and unreasonable processing conditions. Shrinkage and warpage are directly related to residual stress. Transient thermal or curing behavior and material anisotropy can lead to the development of residual stress in machining. This kind of residual stress induced by machining process seriously affects the mechanical properties of products, resulting in warpage or cracks and delamination of composite products.

When the plastic melt is filled, the curing process begins; However, in the post mold filling or pressure holding stage, the flow continues. This results in frozen flow stress, which is of the same order of magnitude as thermal stress. The residual stress of injection molded products includes viscoelastic behavior, flow stress and thermal stress. A considerable part of the flow induced stress comes from the post filling stage of the injection molding process.

5.1.4 Microscopic Properties of Materials

Injection molding process is actually a non isothermal and unsteady flow of compressible viscoelastic polymer melt with phase change in complex flow channel. During this period, due to the different history of material heating and stress, the microstructure (crystallization, orientation, residual stress) of the formed products will be very different from that of the raw materials. Because the injection molding process not

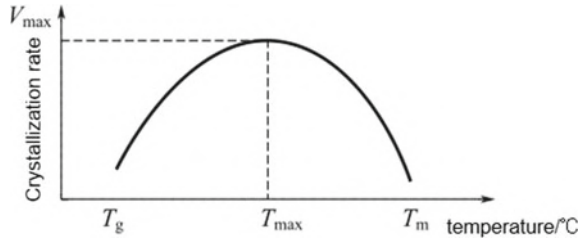
only gives the material a certain shape, but also gives it a specific microstructure, and ultimately determines the performance of the product.

(1) Crystal [12, 13]

Polymers can be divided into crystalline and amorphous according to their aggregation structure. Crystalline polymers are regularly arranged, while non crystalline polymer molecular chains are irregularly amorphous. The criteria for evaluating the crystalline morphology of polymers are crystal shape, size, isotacticity and crystallinity, which play an important role in the physical and mechanical properties of injection molded products.

- ① Effect of crystallization on product properties. The properties of injection molded products are closely related to the microstructure. In terms of microstructure, injection products have non-uniformity, and their macro properties are a complex combination of each microstructure performance.
 - a. Density. The crystallinity is high, the molecular chains are arranged orderly and closely, and the intermolecular force is strong, so the density increases with the increase of crystallinity. For example, the density of 70% crystallinity polypropylene is 0.896 g/cm^3 ; When the crystallinity increases to 95%, the density increases to 0.903 g/cm^3 .
 - b. Tensile strength. The tensile strength increases with the increase of crystallinity. For example, when the crystallinity is 70%, the tensile strength of polypropylene is 27.5 MPa; When the crystallinity increases to 95%, the tensile strength can be increased to 42 MPa.
 - c. Modulus of elasticity. The elastic modulus increases with the increase of crystallinity. For example, when the crystallinity of polytetrafluoroethylene increases from 60 to 80%, its elastic modulus increases from 560 to 1120 MPa.
 - d. Impact strength. The impact strength decreases with the increase of crystallinity. For example, when the crystallinity of polypropylene increases from 70 to 95%, the notch impact strength decreases from 1520 to 486 J/m^2 .
 - e. Thermal performance. The increase of crystallinity is conducive to the increase of softening temperature and thermal deformation temperature. For example, when the crystallinity of polypropylene increases from 70 to 95%, the thermal deformation temperature increases from 124.9 to $151.1 \text{ }^\circ\text{C}$.
 - f. Warping. The increase of crystallinity will reduce the volume and increase the shrinkage. Crystalline materials are more prone to warpage than non crystalline materials. The main reason is that when the products are cooled in the mold, the difference of crystallinity is caused by the difference of temperature, resulting in uneven density and unequal shrinkage, resulting in large internal stress and warpage.
 - g. Gloss. The increase of crystallinity will increase the compactness of the product and improve the surface gloss of the product, but the existence of spherulites will cause the scattering of light waves and reduce the transparency. Taking nylon as an example, when the low-temperature mold is used

Fig. 5.23 Relationship between crystallization speed and temperature



for cooling, the product is rapidly cooled in the mold cavity and becomes transparent due to low crystallinity; If it is formed by high-temperature mold, it becomes translucent or milky white due to further crystallization.

② Effect of injection molding conditions on crystallization [14–16]

- a. Melt temperature. Crystallization is a thermal process. When the melt temperature of polymer is higher than the melting temperature ($T > T_m$), the thermal motion of macromolecular chain increases significantly. When it is greater than the cohesion of molecules, the molecules are difficult to form orderly arrangement and are not easy to crystallize; When the temperature is too low, the motion energy of macromolecular segments is very low, even in the frozen state, and it is not easy to crystallize. Therefore, the crystallization temperature range is between T_g and T_m . In the high temperature region (close to T_m), the nucleation is unstable and the number of nucleation per unit time is small; In the low temperature region (close to T_g), the free energy is low, the crystallization time is long, and the crystallization speed is slow, which can not create conditions for nucleation. In this way, there is a high crystallization rate ($V_{\max}$) and corresponding crystallization temperature ($T_{\max}$) between T_g and T_m , as shown in Fig. 5.23.
- b. Cooling rate. During injection molding, the speed of polymer from above T_m to below T_g is called cooling rate, which determines the existence or generation of crystal nucleus. The cooling rate depends on the difference between melt temperature (T) and die temperature (T_M), which is called undercooling. The undercooling degree is divided into the following three zones.
 - Isothermal cooling zone. When T_M approaches the maximum crystallization temperature ΔT is small, undercooling is small, cooling speed is slow, and crystallization is almost carried out under static isothermal conditions. At this time, molecular chain free energy is large, crystal nucleus is not easy to form, crystallization is slow, cooling cycle is prolonged, and large spherulites are formed.
 - Quick cooling zone. When T_M is lower than the crystallization temperature, the undercooling increases and the cooling speed is very fast. The crystallization is carried out under non isothermal conditions, and the macromolecular chain segments have no time to fold to form a wafer.

At this time, the macromolecular chain relaxation lags behind the speed of temperature change, so the molecular chain forms a loose amorphous region that has no time to crystallize under sudden cooling.

- Medium speed cooling zone. When the mold temperature T_M is controlled between the maximum crystallization rate temperature of the melt and the glass transition temperature, crystallization is generated first in the area close to the surface of the mold. Because the temperature T_M is too high, it is conducive to the growth of crystal nucleus and spherulite in the product, and the crystallization is relatively regular. Therefore, the mold temperature is generally controlled in this area, which has the advantages of large crystallization rate, easy demolding of products and short injection time. For example, the mold temperature of polypropylene is actually controlled between 60 and 80 °C, that is, between T_g and T_{vmax} .

In short, the cooling rate depends on the temperature difference between the melt temperature and the die temperature. The cooling speed is fast, the crystallization time is short, the crystallinity is low, and the product density will be reduced.

- c. Holding pressure. Increasing the holding pressure is helpful to improve the density and dimensional stability of PP parts. However, for the multi-stage pressure maintaining system, the excessive pressure gradient between stages will cause the sudden drop of mold cavity pressure, adversely affect the PP crystallization process, and lead to the decline of crystallinity and mechanical properties.
- d. Injection pressure. The experimental results show that the increase of melt pressure and shear action will accelerate the crystallization process. This is because the stress makes the chain segments oriented along the stress direction to form an ordered region, which is easy to induce many crystal embryos, increase the number of crystal nuclei and shorten the crystallization time, so as to accelerate the crystallization. Therefore, for crystalline polymers, higher crystallinity can be obtained by increasing injection pressure and injection rate during injection molding. Of course, the degree of improvement should be limited to no melt fracture.

When the holding pressure is constant, the injection pressure is significantly lower or higher than the holding pressure, which is unfavorable to the performance of PP parts. When the injection pressure is slightly greater than or equal to the holding pressure, the crystallinity of injected PP is the highest and the mechanical properties are the best.

- e. Orientation. For crystalline polymers, crystallization and orientation are closely related. According to the principle that polymer orientation can improve crystallization, the method of increasing injection pressure and injection rate to reduce melt viscosity can be used to create conditions for crystallization in injection molding practice.

- f. **Vibration.** When considering vibration, it is necessary to distinguish between low-frequency vibration and ultrasonic vibration. In the range of melt under-cooling temperature, ultrasonic vibration can refine the growing grains, and these refined grains can be filled as core points for further growth. The injection molded products with ultrasonic action have higher impact strength, stress cracking strength and transparency.

For low-frequency vibration (vibration frequency less than 100 Hz), local nano free hole integrated microcavity can produce high-frequency phonons (quantum of crystal lattice vibration kinetic energy). Microcavity can play the role of nucleating agent, because microcavity is a small hole in liquid, which is opened in the negative pressure area. When the microcavity collapses, local high pressure can be generated. According to Clapeyron equation, this high pressure can change the melt temperature, which in turn promotes uniform nucleation and crystallization.

In conclusion, the crystallinity of crystalline polymer mainly depends on the setting of injection molding process parameters, and the crystallinity of polymer has an important impact on the performance of products. For the same polymer, the crystallinity is improved, and all other physical and mechanical properties are improved except impact strength. Therefore, in the actual production, the process parameters can be adjusted according to the use requirements of the products, so as to control the crystallinity of the products and achieve the ideal physical and mechanical properties.

- ③ Requirements of crystalline plastics for injection molding machines and molds
 - a. The melting of crystalline plastics requires more energy to destroy the lattice, and more heat needs to be input when transforming solid into molten melt. Therefore, the plasticizing capacity of the injection molding machine should be large, and the maximum injection volume should be increased accordingly.
 - b. The melting point range of crystalline plastics is narrow. In order to prevent the rubber crystallization from blocking the nozzle when the nozzle temperature decreases, the nozzle aperture shall be appropriately increased, and a heating ring capable of independently controlling the nozzle temperature shall be installed.
 - c. Because the mold temperature has an important impact on the crystallinity, the mold water path should be as many as possible to ensure the uniform mold temperature during molding.
 - d. Crystalline plastics have large volume shrinkage in the crystallization process, resulting in large molding shrinkage. Therefore, its molding shrinkage should be seriously considered in the mold design.
 - e. Due to significant anisotropy and large internal stress, attention should be paid to the position and size of gate and stiffener in mold design, otherwise warping deformation is easy to occur, and then it is very difficult to improve by molding process.
 - f. The crystallinity is related to the wall thickness of the plastic part. The wall thickness cools slowly, the crystallinity is high, the shrinkage is large, and

shrinkage cavities and pores are easy to occur. Therefore, attention should be paid to the control of the wall thickness of the plastic part in the mold design.

(2) Orientation [17–19]

- ① Molecular orientation. The molding process of injection molding is divided into three stages: mold filling, pressure maintaining and cooling. The shear stress, normal stress and elastic deformation caused by non isothermal melt flow in injection molding filling and pressure holding stage can not be completely relaxed in the cooling stage, but are “frozen” to form orientation in the product.

During mold filling, the polymer melt flows between the mold cavities, and the wall temperature is generally lower than the glass transition temperature or melting temperature of the polymer. The polymer begins to cool from the moment it begins to enter the mold cavity. A layer of polymer in contact with the mold wall cools rapidly and becomes a non flowing cooling layer with a shear velocity almost equal to zero. The skin layer has an adiabatic effect, so that the polymer close to the skin layer does not solidify immediately and continues to flow forward under the action of shear stress. In this way, a velocity gradient is formed in the mold cavity, so that the two ends of the polymer chain are in different velocity layers, so that the polymer chain is oriented. The longer the holding time, the greater the degree of molecular chain orientation. In the cooling stage, this orientation is frozen, forming a structure with large orientation close to the epidermis and small orientation at the center. In the process of injection molding, the orientation of molecules has an important impact on the physical and mechanical properties of products, and the mechanical properties along the orientation direction are greatly improved.

High melt temperature, high mold temperature, low injection pressure, slow injection rate, and small orientation of injection products; On the contrary, the degree of orientation is large. The mechanical properties in the orientation direction are significantly improved, while the mechanical properties perpendicular to the orientation direction are significantly decreased. Improving the molecular orientation at the center of material flow is beneficial to improve the mechanical properties of products. “Push-pull” injection molding, shear controlled orientation injection and other molding processes are invented based on this principle.

- ② Fiber orientation. The ordered arrangement of fiber macromolecules based on a specific direction (such as fiber axis) is called fiber orientation. Like molecular orientation, fiber orientation will change the mechanical properties of materials, and fiber orientation will make the molded products show obvious anisotropy. The injection speed has a great influence on the fiber orientation. When the melt temperature and mold temperature remain unchanged, the fiber orientation of the products with high injection speed is not as good as that of the products with low injection speed. In the final analysis, the influence of injection process parameters on fiber orientation is the influence on melt viscosity and shear stress in the molding process. Too low or too high melt viscosity is not conducive to

fiber orientation. The increase of shear force is conducive to fiber orientation. Fiber orientation is the result of the combined action of the two.

(3) Residual stress [20, 21]

As mentioned earlier, the shear stress, normal stress and elastic deformation caused by non isothermal flow of melt in injection molding filling and pressure holding stage will also produce flow residual stress when the orientation cannot be completely relaxed in the cooling stage; In addition, during the cooling process, due to the existence of large temperature gradient in the thickness direction of the product, it solidifies at different times, resulting in different shrinkage and thermal residual stress.

Generally speaking, the thermal residual stress is one order of magnitude larger than the flow residual stress. The warpage deformation degree of the product can be predicted from the thermal residual stress, but the contribution of the flow residual stress to the molecular orientation causing the mechanical, thermal and optical anisotropy of the product is dominant, that is, the contribution of the flow residual stress to the molecular orientation is dominant.

Residual stress is an important reason for the shape and size instability of injection molded parts, and also has a significant impact on the service performance of parts, so it has been the focus of research in recent 20 years. The factors affecting the residual stress can be found from the source of residual stress, and it also provides guidance for reducing the residual stress of products in engineering.

From the generation process of flow residual stress, if the molecular orientation caused by flow can reach a new equilibrium state before the melt is “frozen”, the flow stress will not be generated. Therefore, for the injection molding process, the injection temperature, mold wall temperature, melt filling time and filling speed of the melt the holding pressure and the length of the flow channel will affect the flow stress.

It can be seen from the generation process of thermal residual stress that if each part of the injection molded part in the mold cavity can achieve a uniform cooling process, there will be no thermal stress. In the actual injection molding process, due to the shape complexity of products and the process constraints in mold design and manufacturing, it is impossible to completely avoid the generation of thermal stress. Scientific and reasonable design of pressure holding pressure and pressure holding time, layout of cooling pipes, try to make all parts of the workpiece surface solidify at a uniform cooling rate, uniform thickness of mold cavity and avoid large changes, which are some effective measures to reduce thermal residual stress.

5.2 Visualization of the Mold Cavity

Polymer processing is a complex science. In the past, plastic molding was a kind of black box operation. For a long time, a large number of scholars used mathematical methods to study the related theories, and obtained rich academic achievements. However, due to the simplification of physical, thermal or other properties in the process of numerical simulation, there are some differences between the relevant research results and the actual results. Therefore, visualization technology has become an important means to study polymer processing and molding process because it can truly reflect the specific process [22]. By using the periscope light reflection imaging mold, the ultra-high speed camera is used to analyze the instantaneous filling behavior and the visual light source, and a visual molding test bench is created to observe the polarized light and analyze the stress changes in the molding process. Researchers can clearly see the specific changes in the molding process, and the research turns to open box operation. The new technology of visualization will greatly promote the development of plastic forming technology.

The so-called visualization technology is a research method that can directly observe the whole process of polymer molding, such as from solid to molten state, mixing and dispersion, melt cooling and molding. At present, visualization technology has been applied in extrusion, injection and hollow molding.

Visualization method is an important means to study polymer processing and molding process. In the past 20 years, it and CAE technology complement each other and promote the rapid development of polymer processing science and technology. Visualization plays an irreplaceable role in discovering some unknown phenomena in the process of forming and revealing the mechanism of forming defects.

Injection molding visualization technology mainly includes static visualization and dynamic visualization [23].

(1) Static visualization

Static visualization is to process the material before injection and analyze the product after molding. The static visualization technology takes the formed products as the research object, and generally adopts the following two methods: the coloration static visualization method of double barrel and double color injection molding and the magnetization static visualization method of mixing magnetic materials into materials (as shown in Fig. 5.24).

The coloration static visualization method is to inject two different colors of resin into the cavity successively or alternately through the entrance switching device in a molding cycle. The whole molding process can be directly reflected by the distribution of different colors of materials in the molding results.

The principle of magnetic tape recording is applied to the visualization research [24, 25]. Firstly, a certain proportion of magnetic powder is mixed into the resin raw material. During the injection process, a part of the magnetic powder is magnetized by the pulse magnetic field generated by the iron core at the gate position, and then the product slices are put into the magnetic field testing solution for development

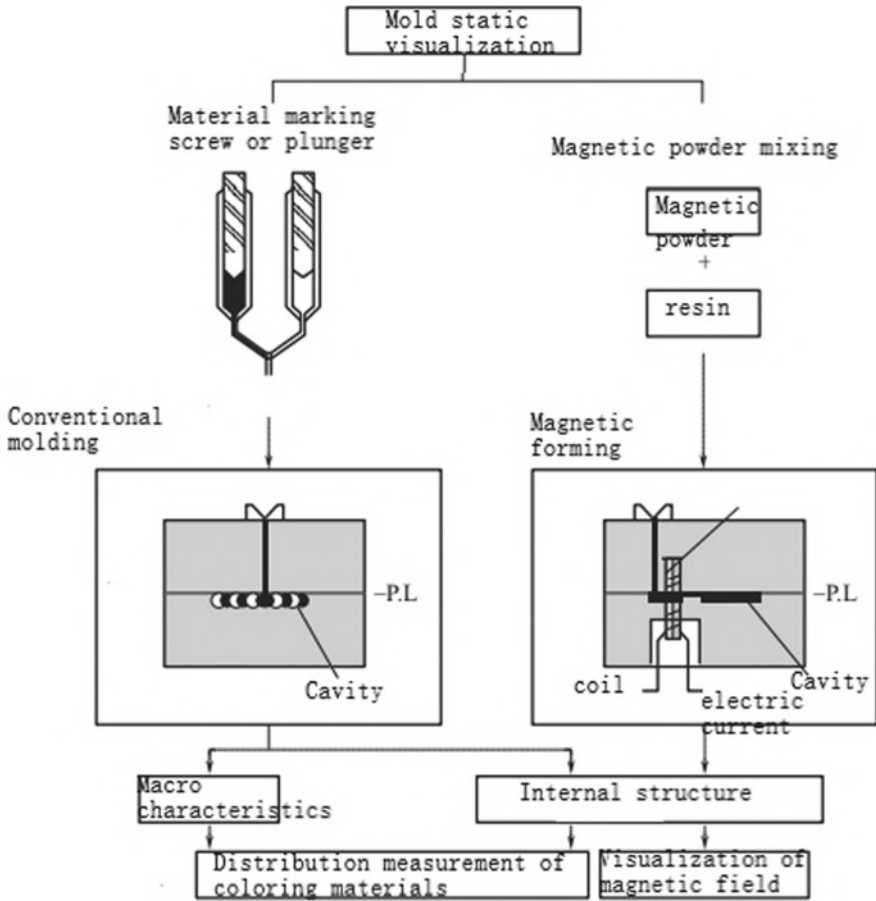


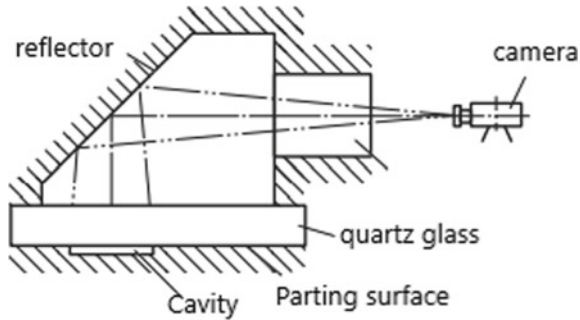
Fig. 5.24 Static visualization method of injection molding

to realize the visualization research. This method can be used to analyze the flow of interlayer, cavity step, compensation flow, low or high speed filling process, the relationship between fiber orientation and flow, the flow state of flow front, semiconductor packaging process and so on. However, the addition of magnetic powder changes the properties of the resin, and the experimental conditions are strict, which affects its application effect.

(2) **Dynamic visualization**

Dynamic visualization technology is to use high-speed camera to directly capture the melt flow in the mold. Through the specially designed visualization mold, the light can enter the mold cavity, and then take the image of the melt filling process through the high-speed camera. The working principle is shown in Fig. 5.25.

Fig. 5.25 Working principle of dynamic visualization

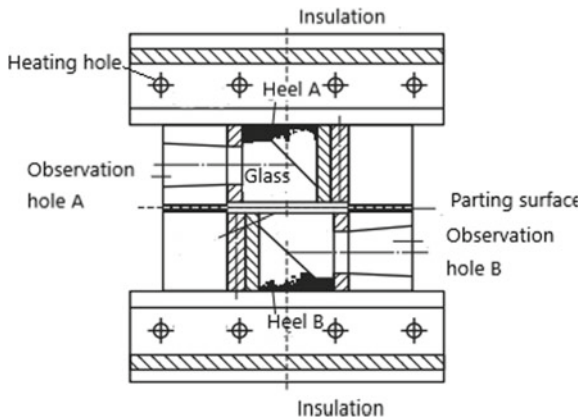


The dynamic visualization technology improves the disadvantage that the static visualization technology can only track the location of materials after processing through the processing of materials before processing and makes the observation of material processing process from the traditional static and process agnostic to recordable and process knowable. Through the real-time observation of the whole injection mold filling process, we can verify whether the past actual processing experience is consistent with the real situation to a certain extent. At the same time, we can also verify the reliability of various simulation software, such as Moldflow, Moldex3D, and evaluate the rationality of the model used in the simulation through the observation of the real mold filling process.

The core part of injection molding visualization technology is injection molding visualization mold [22, 26–29]. The existing visual injection mold can be divided into two categories: observation by transmission light and observation by reflection light.

- ① Visual mold observed by transmission light. The visual mold observed by transmission light is shown in Fig. 5.26. Transparent glass windows are set on the upper and lower surfaces of the mold cavity.

Fig. 5.26 Visual mold viewed with transmission light



In Fig. 5.26, quartz prism windows are set on the fixed mold side and the moving mold side, and the lighting device and the image acquisition device are respectively located on the upper and lower sides of the cavity. When the quartz prism is used in the observation window, the processing difficulty and manufacturing cost of the visual injection mold will be greatly improved, because the quartz glass window is easy to break under the high pressure impact of the plastic melt, so it is difficult to avoid the problem of replacing the quartz glass window for many times. The mold is only suitable for small observation window.

- ② The visual mold observed by reflected light. The visual injection mold is mostly used to observe the filling process of injection molding, so it only needs a transparent glass window on one side of the cavity. As shown in Fig. 5.27, it is designed by the Institute of industry and education of Tokyo University. The visual mold is observed by reflected light. The light enters the cavity observation window through the quartz prism to illuminate the cavity. The irradiation light is reflected by the plastic melt and the metal mold cavity and then returned to the mold cavity, which is collected by the camera device to form an image of the filling situation in the mold cavity area.

The visual mold in Fig. 5.27 uses the glass with trapezoidal section as the observation window. The shape is relatively complex, and the dimensional accuracy of each contact surface of the glass is very high, which greatly increases the difficulty of glass processing. At the same time, the size of the observation hole on one side of the die is small, which limits the size of the observation area.

The visual mold used in this chapter improves and simplifies the original design scheme on the premise that the visual function is not affected. The actual mold is shown in Fig. 5.28, and its structure is shown in Fig. 5.29.

Compared with the original mold, the shape of the glass is changed to cuboid structure, which reduces the complexity of the glass window and is easy to process. At the same time, the observation area is more open, and the lighting source from the observation hole is more sufficient. The original mold uses

Fig. 5.27 Visualized mold viewed as reflected light

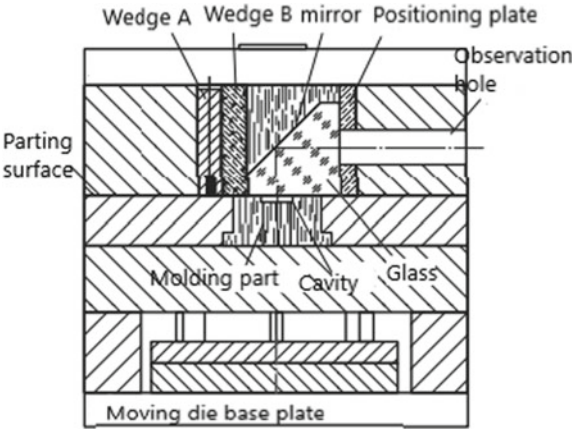
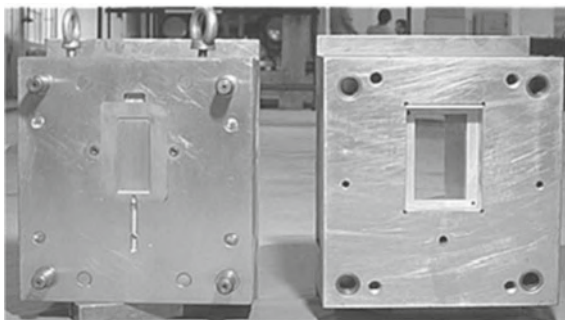
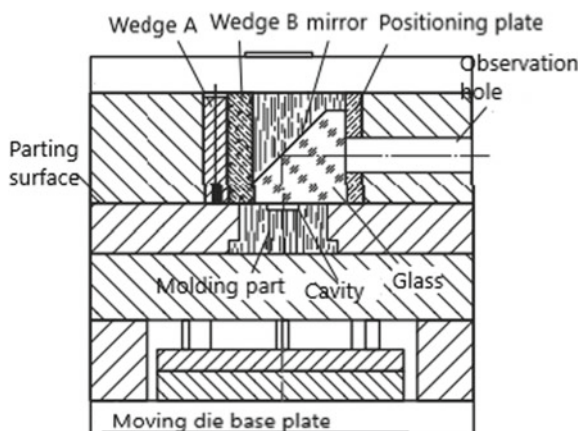


Fig. 5.28 Visual mold**Fig. 5.29** Visual die structure

the way of coating reflective coating on the metal surface to realize the light reflection. In the current mold, the reflector is not affected by other parts as a separate part, The way of fixing the reflector on the reflector improves the light reflection effect and makes the collected image clearer. The most important thing is that the structure of the improved visualization mold is greatly simplified and the cost is greatly reduced.

5.3 3D Copying Defect Generation Mechanisms and Solutions

Injection molding is a system engineering involving mold design and manufacturing, raw material characteristics, pretreatment method, molding process and operation technology. The quality of molded products not only depends on the injection metering accuracy of the injection molding machine and the design and processing technology of the mold, but also is closely related to the processing environment, product cooling time and post-treatment process. Therefore, the molding products

inevitably appear various defects. Through the analysis of the formation mechanism of various defects, it can be seen that the main factors leading to the defects are the material characteristics of plastics, the structure and processing precision of the mold, the injection molding process and the precision of the molding equipment.

5.3.1 Common Defects in Manufactured Products

Generally speaking, according to the appearance quality, dimensional accuracy, mechanical, optical and chemical properties of polymer injection molded products, the common defects of injection molded products can be divided into three categories.

- ① Appearance. It mainly includes weld mark, dent, dark spot, delamination, jet, bubble, flow mark and so on.
- ② Technology. It mainly includes insufficient filling, flash, abnormal ejection, channel mucosa and so on.
- ③ Performance. It mainly includes non-uniform stress (residual stress), embrittlement, warping deformation, non-uniform density and so on.

Common defects of injection products are shown in Fig. 5.30.
The visualization results of common molding defects are shown in Fig. 5.31.

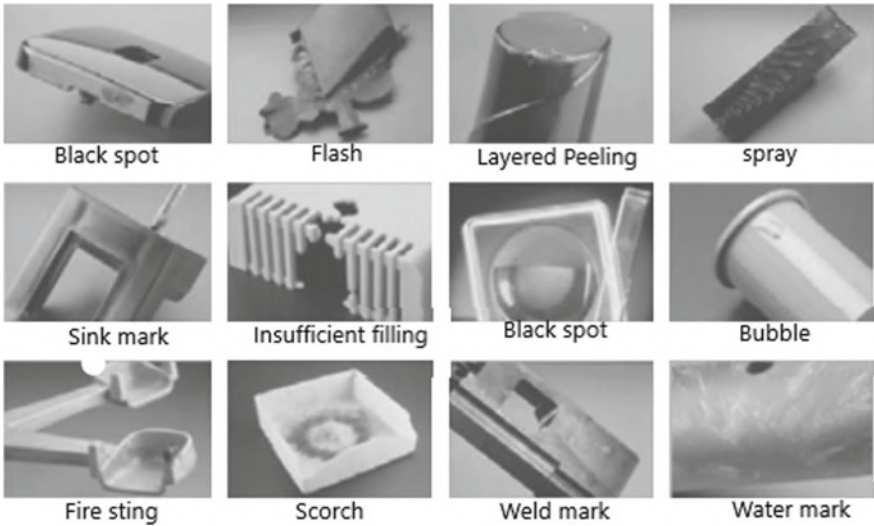


Fig. 5.30 Common defects of injection products

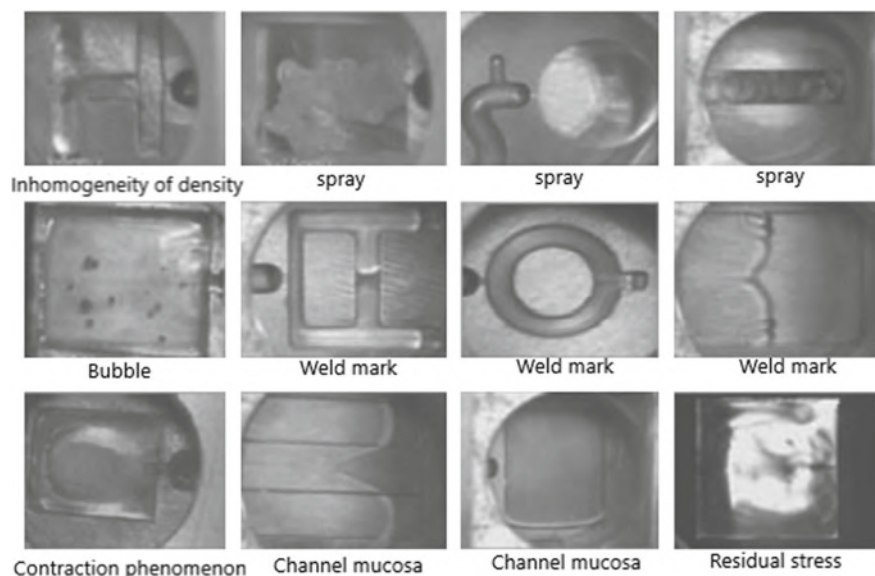


Fig. 5.31 Visualization results of common molding defects

5.3.2 Generation Mechanisms of Typical Defect [30, 31]

In the injection molding process of plastic products, the defects of products are caused by many reasons. In order to discuss the causes of defects, this section will discuss from three aspects: material, process and mold.

- ① **Material.** Improper material selection, volatile gas or other impurities mixed in raw materials, materials not dried, uneven particles, etc.
- ② **Process.** The process mainly includes pressure, temperature, time and speed. The injection pressure, packing pressure and back pressure affect the molding quality. The temperature is mainly the temperature of the mold, the temperature of the nozzle, the temperature of the barrel, and the friction heat generated by the rotation speed of the back pressure screw. Time mainly includes holding time, opening and closing time and plasticizing time. Speed mainly includes screw speed and injection speed.
- ③ **Mold.** It mainly includes pouring method, gate position and size, exhaust, machining accuracy, etc.

Based on the above-mentioned visual mold, the injection molding filling process visualization experimental device used in this chapter is equipped with German Arburg allrounder 270S 500-60 and American GigaView high-speed camera (the shortest exposure time is 21 μ s, maximum frame rate 17,000 fps), the visualization system of the precision injection molding filling process which established by

the image acquisition computer and the professional data analysis and testing software system IMAGEPRO PLUS, in which the visualization mold can easily replace the cavity molding plug-in, as shown in Fig. 5.32, and the application of injection molding visualization technology is introduced by taking the wave flow mark defect in injection molding as an example.

Flow marks are generally divided into wave flow marks and jet flow marks. Flow marks, also known as flow marks, ripple and shock marks, are wavy surface defects on injection products. The phenomena and solutions of wavy flow mark are studied by the visual system of precision injection molding filling process. The product defects are shown in Fig. 5.33. The experimental material is LCI500, NATURALED 76366, and the experimental equipment is Arburg Allrounder 270S 500-60. The process parameters are shown in Tables 5.4 and 5.5. The visualization results of wave current trace are shown in Fig. 5.34.



Fig. 5.32 Visualization system of precision injection molding process

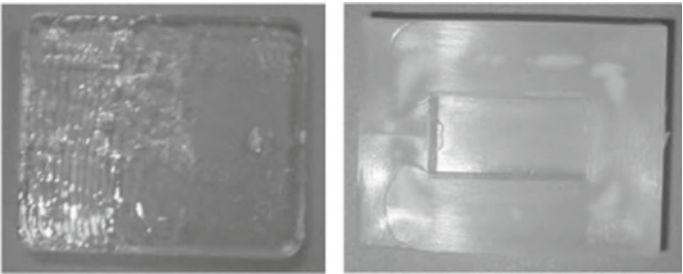


Fig. 5.33 Wave current mark defect

Table 5.4 Temperature setting of rectangular cavity barrel

Feeding section of barrel	Rear section of barrel	Middle section of barrel	Front section of barrel	Nozzle
45	260	280	290	300

Table 5.5 Injection packing parameters setting of rectangular cavity (PC)

Pre-molding position/mm	35	Hold pressure for a period of time/s	0.1
Injection speed/(mm/s)	30	Pressure in the first stage of pressure maintaining/bar	200
Injection pressure/bar	500	Two stage holding time/s	0.1
Turn pressure position/mm	9	Pressure of pressure maintaining section 2/bar	100

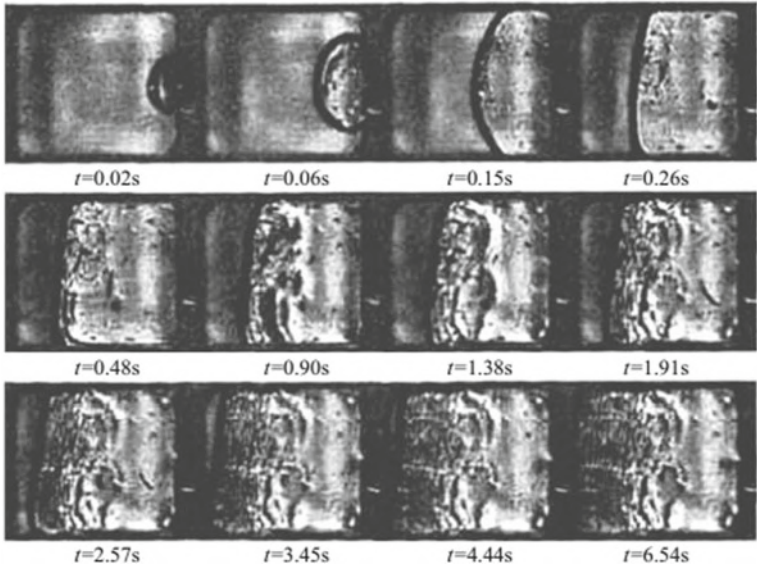


Fig. 5.34 Visualization results of wave current trace (PC)

It can be seen from Fig. 5.34 that the melt flow front enters the cavity relatively quickly, and then flows slowly. The unsteady injection speed leads to the unsteady flow. Because the melt with high temperature meets the mold cavity wall with low temperature during mold filling, a very hard shell is formed, and the shell is sometimes separated from the cavity surface due to the effect of melt flow force, resulting in inconsistent cooling. Finally, wavy marks are formed on the products. The cause diagram of wave current trace is shown in Fig. 5.35.

There is an obvious flow mark at the end of PP product in Fig. 5.35b. The visualization experimental results are shown in Fig. 5.36. The barrel temperature setting is shown in Table 5.6, and the injection packing parameters setting is shown in Table 5.7.

It can be seen from Fig. 5.36 that the melt flows slowly after the speed and pressure switch, and the holding pressure is not stable. At the same time, the melt stays at the speed pressure switching position for a long time, forming a solidified layer and

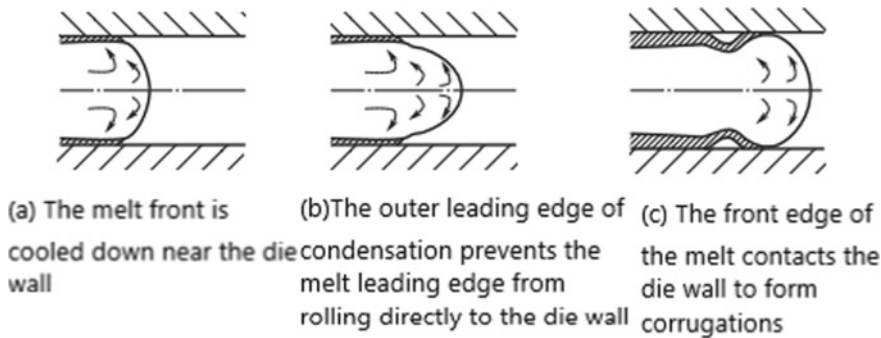


Fig. 5.35 Schematic diagram of the causes of wave current marks

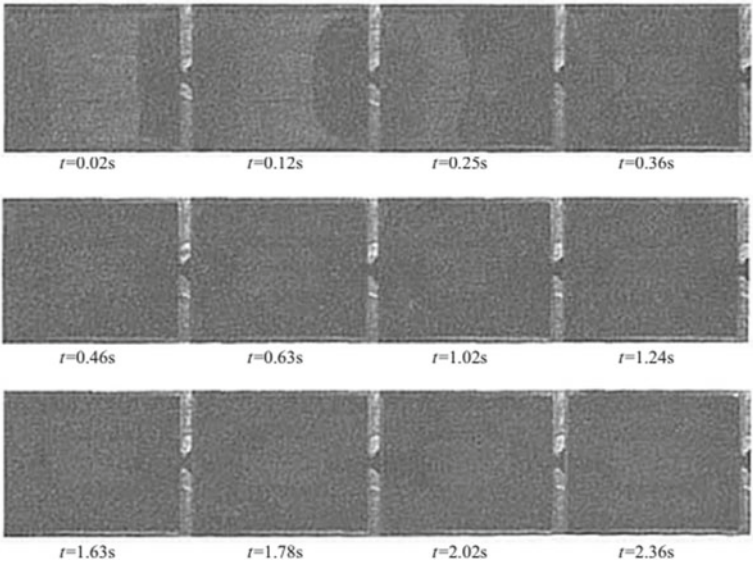


Fig. 5.36 Visualization results of flow marks (PP)

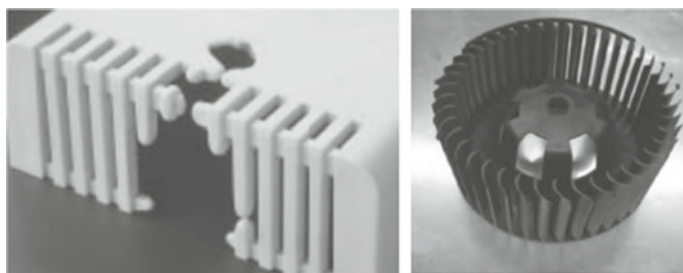
Table 5.6 Barrel temperature setting

Feeding section of barrel	Rear section of barrel	Middle section of barrel	Front section of barrel	Nozzle
45	190	200	210	220

finally forming a ripple. Therefore, improper switching of velocity and pressure, insufficient pressure holding, low or unstable injection speed may lead to wave flow marks.

Table 5.7 Injection packing parameters setting of rectangular cavity (PP)

Pre-molding position/mm	46	Hold pressure for a period of time/s	0.1
Injection speed/(mm/s)	50	Pressure in the first stage of pressure maintaining/bar	300
Injection pressure/bar	500	Two stage holding time/s	0
Turn pressure position/mm	8	Pressure of pressure maintaining section 2/bar	25

**Fig. 5.37** Short shot

5.3.3 Causes and Solutions of Defects in 3D Copied Products

(1) Short shot

The first mock exam is short shot and insufficient filling. It means partial incomplete phenomenon at the end of the material flow or the collapse of the molded part or part of the cavity filled with a part (Fig. 5.37).

① Causes

Material: The plastic has poor fluidity, too long melt flow, too much lubricant or foreign matter in the material.

Mold: The flow resistance increases when the channel size is too small; The runner or gate is too large or blocked; There is no cold well or the cold well is too small; The distribution of runner and gate is not balanced; Poor exhaust of mold; The structure of the product is complex and the local cross section is too thin.

Injection molding machine: The plasticizing amount of injection molding machine is small; The cold material of the nozzle enters the cavity; The inner diameter of nozzle is too large or too small; The plastic frit blocks the feeding channel; Temperature control system failure, the actual material temperature is too low.

② Solution

Material: By selecting the resin with good fluidity; For materials with poor fluidity, adding lubricant can not only improve the fluidity of plastics, but also improve the stability and reduce the gas resistance of gaseous substances.

Mold: Adjust the gating system design. If the gate position is changed, the gate size will be enlarged and shortened, the runner size will be widened and shortened, and the cooling well will be enlarged; The nozzle is well matched with the die mouth to improve the exhaust of the die.

Molding process: Change the molding conditions. Such as increasing injection temperature, injection pressure, injection rate, packing pressure, mold temperature, extending packing switching time, etc.; Increasing the back pressure can increase the intermolecular resistance and shear heat of melt, which is conducive to better plasticizing materials.

Injection molding machine: Check injection molding equipment. Equipment failure and screw barrel wear may cause under injection phenomenon.

(2) Flashes

Flash, also known as overflow, overflow and drape, mostly occurs at the parting and closing position of the mold, such as parting surface, sliding mechanism, vent hole, vent thimble, gap of insert, and hole of ejector pin (Fig. 5.38).

① Causes

Material: If the viscosity of the material is too low, the water absorbent or water sensitive plastics will greatly reduce the flow viscosity, thus increasing the possibility of flash; The high viscosity of the material results in the increase of the flow resistance, the increase of the back pressure, the increase of the cavity pressure and the insufficient clamping force.

Mold: Foreign matters on parting surface or protruding burr around formwork; The accuracy of parting surface is poor, and the movable template is warped; The rigidity of the die is insufficient; If the mold design is unreasonable and the



Fig. 5.38 Flashes

opening position of the mold cavity is too deviated, the tension will be produced on one side of the mold during injection, which will cause flash.

Molding process: The injection volume is too large; The injection pressure is too high or the injection speed is too fast; The setting of clamping force is too low; The holding pressure is too high and the speed pressure switch is too late; The melt or mold temperature is too high.

Injection molding machine: The clamping force of injection molding machine is insufficient; The clamping device is not well adjusted and the clamping force is not evenly applied; The check ring is worn seriously, or the barrel and screw are worn too much; The parallelism of the die is not good, the installation is not parallel, or the force and deformation distribution of the pull rod is uneven.

② Solution

In terms of equipment, choose the injection molding machine with good clamping mechanism rigidity and clamping force meeting the standard, and the injection molding machine with multi-stage injection or feedback control system is the best choice. In terms of molding conditions, we can start from reducing the fluidity.

- a. If the flash phenomenon occurs in the filling stage, the possible solutions are as follows: If the die is damaged or the parting surface has error, the die needs to be modified; Properly reduce the injection speed or the temperature of the plastic; The heating deformation of the die can be reduced by adding a gasket in the center of the die plate.
- b. If the flash phenomenon occurs in the feeding stage, the possible solutions are as follows: Reduce the feeding pressure or feeding rate, and check whether the clamping force is appropriate; The injection speed is too slow and the material has a large effective viscosity, which leads to the increase of pressure loss in the cavity. Check and analyze the causes of the change of effective viscosity of materials, and adjust the injection process according to the specific causes; Detect the deformation of the mold, solve the deformation of the mold.

(3) Filling unbalance

For injection molding, the first mock exam is often caused by the imbalance of filling (Fig. 5.39). The balance of filling must be considered in the design of multi cavity mold. In the multi cavity injection mold, the runner system is usually designed as “H” shape. Because the runner is geometrically symmetrical, it is also called “geometric balance” or “natural balance” runner system design.

- ① Causes. Because the shear heat generation has an obvious effect on the melt temperature distribution in the channel, the unbalanced temperature distribution is the fundamental reason for the filling imbalance. In low speed injection, the time of melt flowing through the channel is relatively long, and the heat loss of resin along the channel wall is more. Therefore, the overall temperature value is lower than that in high speed injection, and the melt temperature distribution gradually decreases from the high temperature region of the core to the channel

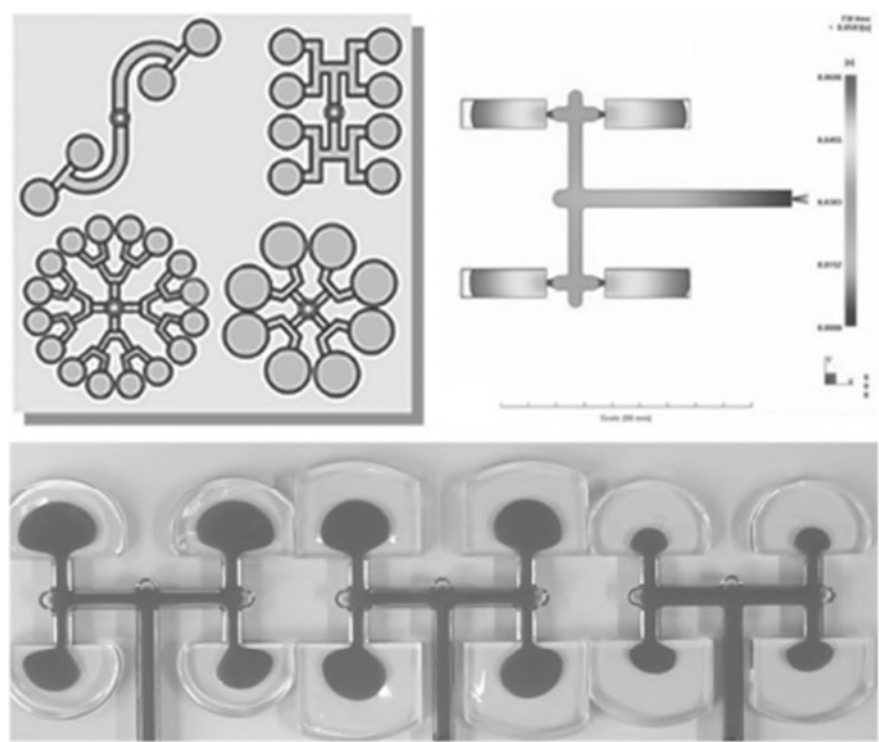


Fig. 5.39 Channel filling imbalance

wall. When filling at low speed, the high temperature zone of melt tends to the upper die wall, so the filling of upper die cavity is faster (Fig. 5.40). During high-speed injection, the time of melt flowing through the channel becomes shorter, the heat loss along the channel wall is reduced, and the shear heat generation effect is obvious. Therefore, the overall temperature distribution value is higher, and the closer the channel wall is, the greater the shear rate is, and the more significant the shear heat generation is (Fig. 5.41). The temperature

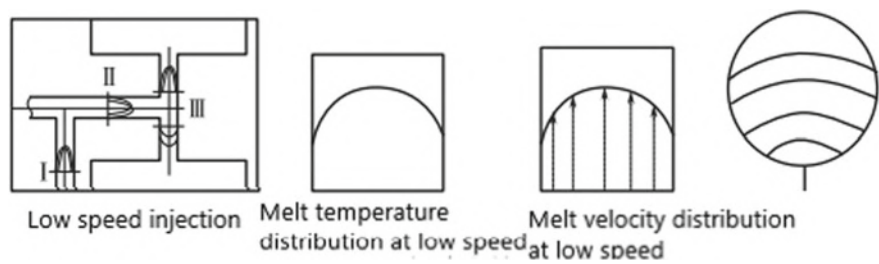


Fig. 5.40 Low speed filling imbalance

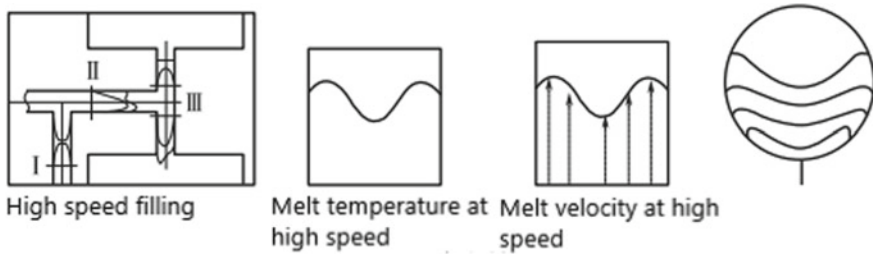


Fig. 5.41 High speed filling imbalance

near the wall of the channel increases to form a wave crest, while the core is a relatively low temperature area of the basin. At high filling speed, the high temperature zone of melt tends to the lower die wall, so the filling of lower die cavity is faster.

- ② Solutions. The fundamental problem of Filling Imbalance in multi cavity injection mold is to improve or eliminate the asymmetry of melt temperature distribution in the flow plane.
 - a. The wall thickness of the product is uniform, and the gate position is as far away from the thin wall position of the product as possible.
 - b. The designed runner takes into account both geometric balance and rheological balance, and the gate position and runner layout are optimized by CAE software simulation analysis.

(4) Sink marks

Shrinkage mark is the local collapse of the product surface, also known as dent, shrinkage pit and settlement spot. When the thickness of plastic parts is uneven, some parts will produce shrinkage marks due to excessive shrinkage during cooling. However, if the surface is hard enough during cooling, the shrinkage in the plastic part will often cause structural defects. Shrinkage marks are easy to appear far away from the gate and at the thick wall, rib, boss and embedded parts of the product (Fig. 5.42).

- ① Causes. The shrinkage mark is mainly caused by the material shrinkage is not compensated, and the crystalline plastics with large shrinkage are easy to produce shrinkage marks. The holding pressure, holding time, melt temperature and cooling rate all have a great influence on the shrinkage mark, and the insufficient holding pressure is the important reason.

Material: material shrinkage is too large.

Mold: unreasonable product design, excessive or uneven wall thickness; The gate position is unreasonable, the gate is too small or the flow channel is too narrow or shallow, and the melt filling process cools too early; Multi gate mold shall be provided with gates symmetrically; If the mold cooling is uneven, effective cooling water channel shall be set at the key parts of the mold.

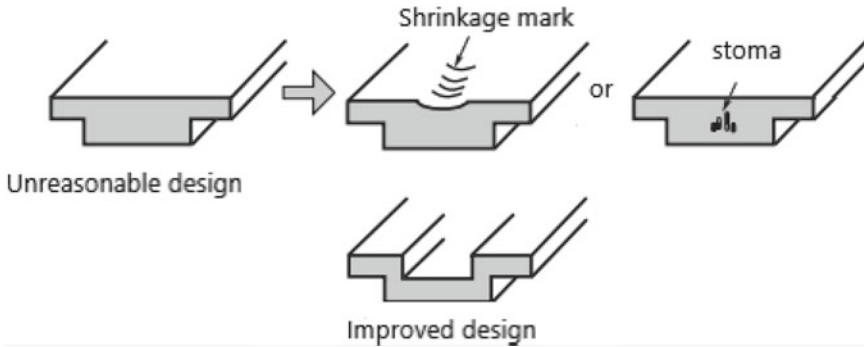


Fig. 5.42 Shrinkage marks and cavities

Molding process: insufficient injection volume and insufficient feeding; The injection speed is too fast, the injection time or pressure holding time is too short, and the gate is not solidified at the end of pressure holding; The injection pressure or holding pressure is too low; If the melt temperature is too high, shrinkage marks are easy to appear at the wall thickness, stiffener or convex back. Injection molding machine: the screw is seriously worn, and leakage occurs during injection and pressure holding, which reduces the mold filling pressure and material quantity, resulting in insufficient melt; The nozzle hole size is too large or too small. Too small is easy to block the feed channel, too large will cause too small injection pressure and difficult mold filling.

② Solutions

Materials: change the raw materials with small shrinkage; Nucleating agent is added to crystalline plastics to accelerate crystallization.

Mold: the wall thickness shall be uniform during design, and sudden change of wall thickness shall be avoided as far as possible; Set up effective cooling water channel to ensure the cooling effect of products; Adjust the mold filling speed of each gate and set up symmetrical gates.

Molding process: increase the injection speed to fill the product and eliminate most of the shrinkage; Adjust the injection volume, speed and pressure switching position; Increasing the back pressure and retaining a certain cushion in the front section of the screw are conducive to reducing the shrinkage phenomenon; Increase the injection pressure and holding pressure, adjust and optimize the holding pressure curve; Increase the injection and pressure holding time, prolong the cooling residence time of products in the mold, and maintain a uniform production cycle; Reduce melt temperature and die temperature.

(5) Weld line

The weld line is also called weld line and weld joint (Fig. 5.43). During mold filling, when two opposite or parallel melt fronts meet, the weld line will be formed. Weld marks not only affect the appearance quality of plastic parts, but also affect the

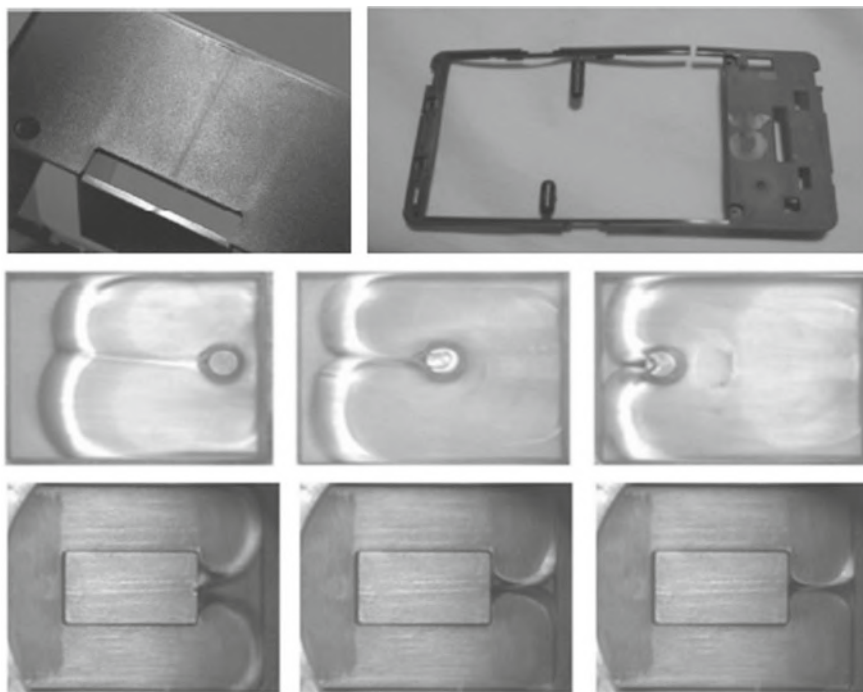


Fig. 5.43 Weld line

mechanical properties of plastic parts, such as impact strength, tensile strength and elongation at break. Generally, the smaller the included angle (welding angle) at the front end of the two converging melts, the more significant the welding line and the worse the product quality. When the welding angle reaches 120° – 150° , the welding line disappears.

- ① **Causes.** Weld line is a common plastic defect. Its existence not only affects the appearance quality of products, but also has a great impact on the mechanical properties of products, especially on fiber reinforced materials and multiphase blend polymers.

Material: plastic has poor fluidity, and the melt front converges after a long time to produce obvious weld marks.

Mold: the flow channel is too thin and the cold charging well is small; Poor exhaust; The product wall thickness is too small or the difference is too large; The gate section and position are unreasonable, resulting in too small wave front confluence angle; Mold temperature is too low.

Injection molding machine: poor plasticization and uneven melt temperature; Melt leakage occurs during injection and pressure holding, which reduces the mold filling pressure and material volume.

- ② Solutions. The weld line is essentially the combination of two plastic flow fronts without complete fusion. To eliminate and solve the welding line, the viscosity of the plastic must be low enough, the temperature must be high enough, the pressure must be high enough, and the plastic must be kept for enough time for complete welding. Generally, in the case of good exhaust, accelerate the filling and feeding speed, and increase the pressure as soon as possible after the combination of the two plastic flow fronts, which is helpful to solve the problem of weld lines.

Materials: properly add lubricants and stabilizers to plastics with poor fluidity or high heat sensitivity, and use plastics with good fluidity or high heat resistance if necessary; Raw materials should be dried and liquid additives in the formula should be minimized.

Mold: if the mold temperature is too low, properly increase the mold temperature or purposefully increase the local temperature at the fusion joint; Change gate position, number and size, cavity wall thickness and runner system design to change the position of fusion line; Open, expand or dredge the exhaust channel, including exhaust through the gap of insert and thimble.

Molding process: increase injection pressure and holding pressure; Set a reasonable injection speed, high speed can make the melt reach the confluence before cooling, and low speed is conducive to the discharge of air in the mold cavity; Reduce clamping force to facilitate exhaust; Set the temperature of the barrel and nozzle reasonably. The temperature is high, the viscosity of the plastic is small, the flow state is unobstructed, the welding mark becomes shallow, and the temperature is low, so as to reduce the decomposition of gaseous substances; Increase the screw speed to reduce the plastic viscosity; Increase the back pressure to increase the density of plastic.

(6) Jetting

Jettings are one of the flow marks, which bend like a snake from the gate along the flow direction (Fig. 5.44). It is mainly because of the injection rate. After the plastic enters the gate and before contacting the cavity, it does not encounter obstacles, flies for a long distance and cools rapidly.

- ① Causes. When the molten material flows through the narrow area such as nozzle, runner or gate at high speed, it suddenly enters the open and relatively wide area. The melt bends along the flow direction, advances like a snake, and cools rapidly after contacting the die surface. If this part of the material can not be well integrated with the subsequent resin entering the cavity, it will cause obvious jet lines on the product.

Material: brittle material will aggravate the spray mark; The wall thickness difference of the product is too large, and the melt flows rapidly from the thin part to the thick part, resulting in unstable flow, which may produce jet.

Mold: the gate position and type design are unreasonable and the size is too small; The runner size is too small; The cross-sectional area from gate to cavity increases suddenly, the flow is unstable, and it is easy to produce jet.

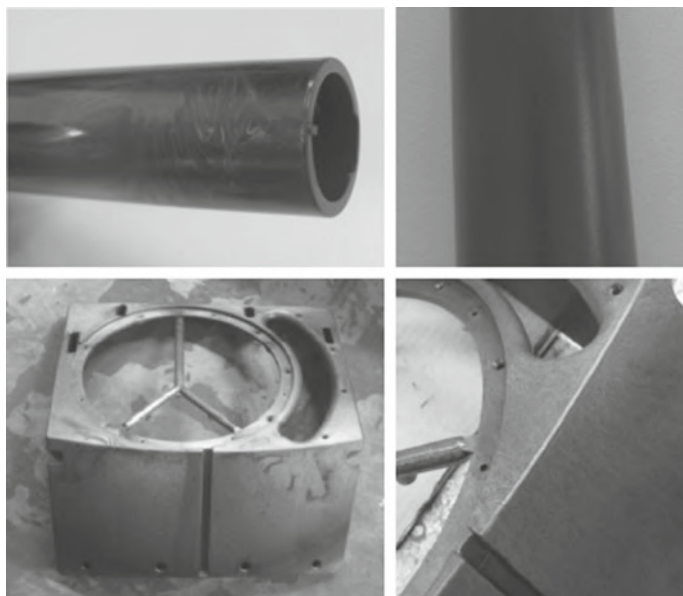


Fig. 5.44 Jetting

Molding process: excessive injection speed; Excessive injection pressure; Melt temperature and die temperature are too low.

- ② Solutions. Expanding the gate cross section or reducing the injection rate are optional measures. Generally, the method of reducing the injection speed and plastic viscosity can also be used. In addition, increasing the mold temperature can also alleviate the cooling rate of the resin in contact with the cavity surface and prevent the formation of case hardened skin at the initial stage of filling. The thorough solution is to modify the gate structure or add inserts in the cavity to make the plastic form a typical fountain flow after encountering obstacles.
- Material: select the appropriate material, and the spray mark of brittle material is more obvious.

Mold: set reasonable gate position to avoid spraying, try to avoid entering deep, long and wide areas to avoid spraying; Properly increase the gate size to avoid spraying; Use the appropriate gate type to avoid spraying, such as fan gate, membrane gate, ear guard gate, lap gate, etc.

Molding process: reduce injection speed and injection pressure; Using multi-stage injection speed to make the melt front pass through the gate at low speed, and then increase the injection speed after the melt flows through the gate, which can eliminate the injection phenomenon to a certain extent; Increase the melt temperature and die temperature to improve the fluidity of materials in the filling process.

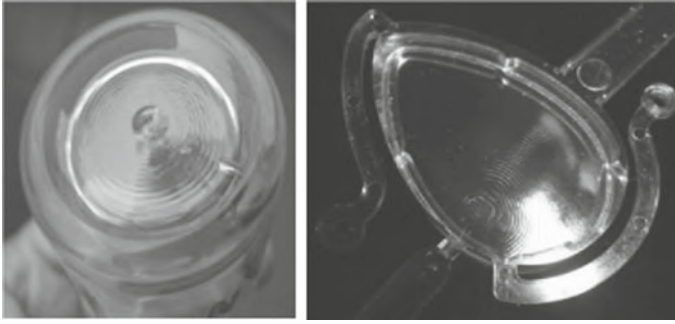


Fig. 5.45 Flow mark

(7) Flow mark

Wave flow mark, also known as flow mark, ripple and shock mark, is a wavy surface defect on injection products (Fig. 5.45). Wave flow mark is caused by the increase of resistance between the central flow layer of plastic products and the solidification layer on the cavity surface, resulting in the wrinkling of the solidification layer on the cavity surface. It is usually caused by the increase of viscosity caused by too slow plastic flow speed.

- ① Causes. The formation mechanism of wave current trace is shown in Fig. 5.46. During injection molding, because the melt front cools down near the mold wall, the condensed outer front prevents the melt front from turning directly to the mold wall, and then the melt front contacts the mold wall again. After such repetition, ripples are formed.

Materials: poor material fluidity and poor lubricant selection.

Mold: the cold well is too small, and the material with too low temperature enters the cavity; Poor exhaust; Excessive resistance in the cavity; The runner or gate is too small, the shear rate and shear stress are large, and the melt filling is unstable.

Molding process: when the injection speed is high, the melt filling is unstable; When the injection speed is low, the solidified layer extends to the leading edge; The injection speed is too low, which makes the melt temperature drop too fast in the filling process; Improper switching of V/P switching voltage.

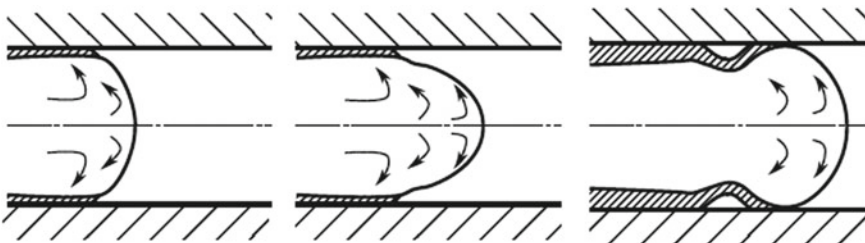


Fig. 5.46 Formation mechanism of flow mark

Injection molding machine: during injection and pressure maintaining, molten material leaks, reducing mold filling pressure and material volume, resulting in insufficient material supply; Check ring and screw are seriously worn.

② Solutions

Materials: select appropriate materials and low viscosity resin if conditions permit.

Mold: adjust and optimize the cold charging well to prevent low-temperature materials from entering the cavity; Appropriate gate section shall be adopted, and the gate and runner section shall preferably be circular to reduce the flow resistance of flowing material; Proper gate type shall be adopted to avoid flow pattern, preferably handle type, fan-shaped or diaphragm type; Improve the exhaust conditions of the die.

Molding process: select appropriate injection speed and injection pressure; Increase the melt temperature and die temperature to improve the fluidity of materials in the filling process.

Annual ring wave flow mark: increase the temperature of mold and nozzle, and improve the injection rate and mold filling speed; Increase injection pressure and holding time; Properly expand the sectional area of gate and runner (if gate is set in the weak area of plastic parts, square section shall be adopted).

Spiral wave flow mark: multi-stage injection speed is adopted, and the injection speed is controlled by slow, fast and slow grades; Properly expand the section of runner and gate to reduce the flow resistance of flowing material; Properly increasing the temperature of barrel and nozzle is conducive to improve the flow performance of molten material.

Cloud wave flow mark: appropriately reduce the temperature of the mold and barrel, improve the exhaust conditions of the mold, reduce the material temperature and mold filling rate, appropriately expand the gate section, and consider changing the lubricant variety or reducing the quantity.

(8) Clod flow lines

Clod flow lines, also known as sun spot and fog spot, refers to the circular color change near the gate (see Fig. 5.47). The shape is oval or round, which is usually determined by the pouring method and gate size, which is caused by melt fracture.

- ① Causes. The reasons for gate halo are diverse, and the main reasons are too high injection pressure and too low mold temperature. Too low mold temperature will cool the plastic too fast, resulting in too much cold material, and then rush to the product surface, resulting in defects; The temperature of barrel, nozzle and die is low; Gate setting is unbalanced; The gate is too small or the cavity at the pouring place is too thin. When the glue flow is large and the cross-sectional area is small (gate and cavity meat thickness), the shear rate is large, the shear stress increases, and leads to the rupture of the melt glue, resulting in gate halo. The rupture of melt adhesive will also lead to flow marks, color change, fog spots and other defects.

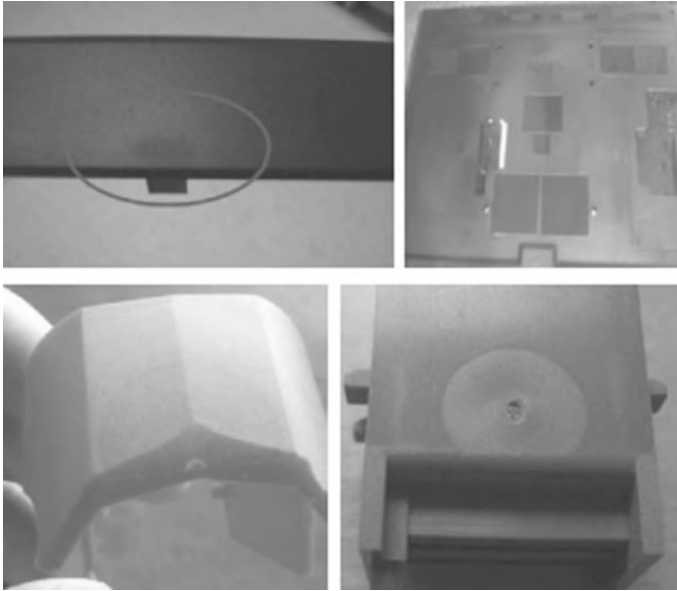


Fig. 5.47 Clod flow lines

② Solutions

Mold: adjust the gate position so that the gate does not affect the appearance quality of products as much as possible; Appropriate gate section shall be adopted, and the gate and runner section shall preferably be circular to reduce the flow resistance of flowing material; With proper gate type, the effect of side pouring and lap pouring is better than that of latent pouring; Reasonable layout of cold charging well.

Molding process: reduce injection speed and injection pressure, and adopt multi-stage injection pressure and position exchange; Increase the melt temperature and die temperature to improve the fluidity of materials in the filling process.

Simulation analysis: the temperature, shear rate and shear stress when the melt passes through the above narrow area can be predicted through numerical simulation. According to the analysis results, the appropriate gate size and cavity wall thickness can be found out quickly.

(9) Burn mark

The appearance of burn marks is mostly caused by the overheating and decomposition of materials. During mold filling, when the air in the mold is compressed, the temperature rises and burns the polymer, resulting in scorch and coke marks. Such defects often occur at the fusion joint, and it can be found that the product surface shows silver and light brown dark stripes (Fig. 5.48).



Fig. 5.48 Burn mark

- ① Causes. Scorched dark lines are caused by overheated decomposition of molten materials. Light brown dark lines are due to oxidation or decomposition of molten material. These degraded melts will lead to the decline of mechanical properties of products.

Materials: high content of volatiles in materials; Excessive amount of volatile lubricant and release agent; Excessive impurities or contamination of materials and too much recycled materials; The particles are uneven and contain powder.

Mold: poor mold exhaust; Small gate or improper position; Poor exhaust and dead angle in flow channel system; The local pressure in the cavity is too high and the material flow converges slowly, resulting in difficult exhaust.

Molding process: the injection pressure or pre plastic back pressure is too high; The injection speed is too fast or the injection cycle is too long; The screw speed is too fast, resulting in overheating; Barrel nozzle temperature is too high; The molten resin in the barrel stays too long, resulting in decomposition.

Injection molding machine: the barrel is not cleaned; Poor accuracy of heating system leads to overheating and decomposition of materials; The accumulated material is decomposed by heating due to the defect of screw or barrel; The melt in the nozzle or screw, check valve and other parts is retained and decomposed.

- ② Solutions

Materials: select appropriate materials; Appropriate use of volatile lubricant and release agent.

Mold: improve the exhaust of injection molding machine and mold to ensure that the gas generated when materials are filled into the mold during injection can be discharged smoothly outside the mold.

Forming process: the melting temperature is too high to reduce the barrel temperature; Hot runner temperature is too high, check hot runner temperature, reduce hot runner temperature; If the molten material remains in the barrel for too long, a small diameter barrel is used; If the injection speed is too high, reduce the injection speed and adopt multi-stage injection; Reduce injection pressure and screw pre plastic back pressure; Reduce the injection speed and shorten the injection cycle.

Injection molding machine: reduce the melt temperature and shorten the residence time of materials in the barrel to prevent the decomposition of materials

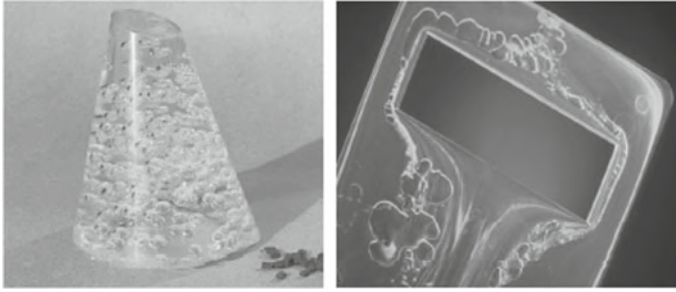


Fig. 5.49 Bubble

due to overheating; After injection of thermosensitive plastic, clean the barrel; Ensure the cleanliness of injection molding workshop, injection molding machine and mold; Adjust to the appropriate screw speed to minimize the entry of gas with appropriate back pressure.

(10) Bubble

Bubbles, also known as air pockets, air marks and pores, can be divided into blisters and air pockets. Bubbles are caused by the presence of gas in the mold cavity. During the melt flow process, the gas will gather in some parts of the mold cavity. If these gases cannot be discharged smoothly and the gas is trapped in them, they will form bubbles, or these parts of the mold cavity cannot be filled to form air pockets (Fig. 5.49).

- ① Causes. The formation of cavitation is due to the rapid surface cooling and slow center cooling of some thick wall products, resulting in uneven volume shrinkage and the formation of cavities in the thick part of the wall. The formation of bubbles is due to the fact that the moisture and gas in the plastic cannot be eliminated during the cooling process of the product, resulting in the formation of bubbles inside the product. Even if the melt can fill these areas, the melt often produces coke marks due to the high temperature of the surrounding gas, which affects the surface quality of the product. Therefore, the bubble phenomenon can be eliminated by adjusting the gating system design or injection molding process.

Materials: poor fluidity of materials and insufficient drying of plastics.

Mold: the wall thickness of the product changes rapidly, and the cooling rate of each part is inconsistent, which is easy to produce bubbles; Poor mold exhaust, or insufficient and blocked exhaust duct, poor position, etc.; Defects in mold design, such as poor gate position, too small gate, asymmetric arrangement of multiple gates, too thin runner and unreasonable mold cooling system.

Molding process: the injection speed is too fast, and the melt is decomposed by shear; The plasticizing process is too fast; The injection pressure is too small; Melt temperature and die temperature are too high.

Product: the wall thickness of the product is too large, and the cooling speed inside and outside is different; Large difference in wall thickness of product

section, the melt in the thin wall flows slowly, and the melt in the thick wall entraps the gas in the mold cavity to form cavitation.

- ② **Solutions.** To eliminate bubble defects, it is first necessary to determine the source of gas in the plastic: water vapor is because the plastic is not dry well; Air is due to insufficient back pressure or too large ejection distance.

Materials: select appropriate materials; Fully dry the materials; For volatile plastic additives, it is necessary to change the melt temperature or plastic additives.

Mold: improve the exhaust of mold; Appropriately increase the size of main flow channel, shunt channel and gate.

Molding process: extend the holding time and increase the mold temperature; For molded products with large thickness change, reduce the injection speed and increase the injection pressure; Adjust the back pressure reasonably to prevent air from entering the material.

(11) Sliver mark

Sliver mark, also known as silver thread and silver wire, is a splash like trace formed on the surface of the product due to the volatilization of air or moisture in the plastic, or burning due to the mixing and decomposition of heterogeneous plastics (Fig. 5.50). During mold filling, volatile gases are precipitated along the wave front. These gases are often decomposed by material heating or water vapor. The gas bursts at the front and is stretched into silver stripes after being distributed on the product surface to form stripes on the product surface. These crazes usually form a V-shape with the tip facing away from the gate.

- ① **Causes.** When the moisture content is too large, heating will produce water vapor. During plasticization, due to the unfavorable operation of the screw, the air carried by the material cannot be discharged, resulting in crazing. In some cases, large bubbles are elongated into flat bubbles, which cover the product surface and peel the product surface. Sometimes, because the temperature gradient from the barrel to the nozzle is too large, the shear force is too large, and crazing will also occur. **Material:** poor material fluidity and high viscosity; Raw materials are poorly dried and mixed with water or other materials.



Fig. 5.50 Sliver mark

Mold: poor mold exhaust; The cold well is too small. During injection, the cold material is brought into the mold cavity, and part of it is quickly cooled and solidified into a thin layer; Water leakage of mold temperature control system; Condensation water is formed on the die surface; The gate and runner are too small or deformed, and the material is decomposed after the injection speed is too fast.

Molding process: the material stays too long and decomposes over heat; The injection speed is too fast and the pressure is too high; Melt temperature is too high to decompose; The pressure holding time is too short; The screw speed is too fast and the shear rate is too large; The injection time is too long; Mold temperature is too low.

- ② Solutions. In terms of materials, select materials with low moisture absorption, or use good drying equipment to fully dry the materials; In terms of technology, reduce the melt temperature, stabilize the nozzle temperature, increase the back pressure during plasticization, and select the screw with large compression ratio; The die is provided with an exhaust slot, so that the gas can be easily discharged from the cavity.

Materials: check whether the raw materials are polluted by other resins and fully dry; Completely remove the old material from the barrel during refueling; Select materials with good fluidity.

Mold: improve the exhaust of injection molding machine and mold; Appropriately increase the size of main flow channel, shunt channel and gate.

Molding process: reduce material residence time, reduce melt temperature and prevent material decomposition caused by excessive temperature; Reduce screw speed, injection speed and injection pressure; Increase the back pressure to prevent air from entering the material; Adopt multi-stage injection, medium speed injection to fill the runner → fill the gate slowly → fast injection → fill the mold slowly at low pressure, so that the gas in the mold can be removed in time in each section; Raise the mold temperature.

(12) Lusterless

Lusterless is also called discoloration and poor gloss (Fig. 5.51).

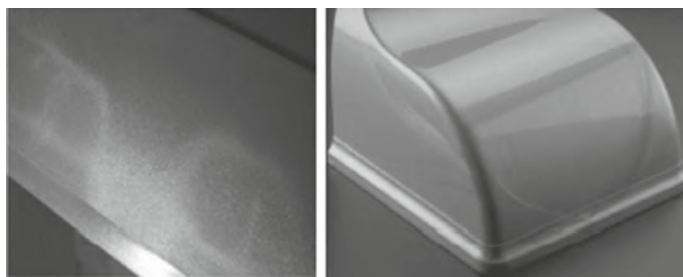


Fig. 5.51 Lusterless

- ① Causes. Color difference is a common defect in injection molding. There are many factors affecting color difference, including raw material resin, color masterbatch, mixing of color masterbatch with raw materials, injection molding process, injection molding machine, etc.

Materials: materials are contaminated; High content of water and volatile matter; Decomposition of colorants and additives; Insufficient color or color masterbatch or uneven dispersion; There are color differences in different batches of raw materials and color masterbatch.

Mold: poor mold exhaust and material burning; Mold gate is too small; The size of main flow channel and diversion channel is too small; There are dead corners in the die structure.

Molding process: the screw speed is too high and the pre plastic back pressure is too large; Uneven temperature of barrel and nozzle; The injection pressure is too high, the injection time is too long, and the injection speed is too fast, which makes the products change color; If the mold temperature is too low, the solidified layer is overstocked or pushed and pulled to produce fog marks, resulting in color difference.

Injection molding machine: there is dust pollution on the equipment, causing material discoloration; Failure of equipment heating system; There are obstacles in the barrel to promote the degradation of materials; There are foreign matters in the barrel or screw groove, causing the material to change color after grinding.

- ② Solutions

Materials: control raw materials, strengthen the inspection of raw materials and color masterbatch in different batches, and eliminate the influence of raw materials and color masterbatch; The amount of volatile lubricant and release agent is appropriate.

Mold: solve the problem of color difference caused by mold gating system and exhaust slot through the maintenance of corresponding molds.

Molding process: master the influence of barrel temperature and color masterbatch on product color change, and determine its change law through color test process; Avoid the color difference caused by local overheating and decomposition of materials, and strictly control the temperature of each heating section of the barrel, especially the nozzle and the heating part close to the nozzle; If the injection speed is too high, reduce the injection speed; Multistage injection; Reduce injection pressure and screw pre plastic back pressure to prevent shear overheating.

Injection molding machine: select the injection molding machine with appropriate specification to solve the problems such as material dead corner of the injection molding machine; The heating part shall be inspected frequently during production, and the damaged or out of control components of the heating part

shall be replaced and repaired in time to reduce the probability of color difference; Ensure the cleanliness of injection molding workshop, injection molding machine and mold; Adjust the appropriate screw plasticizing speed.

(13) Whitening

The main reason for the whitening phenomenon is that the external force acts on the surface of the product, resulting in stress whitening and poor demolding effect. Albinism most often occurs at the ejection position of ABS resin products (Fig. 5.52).

- ① Causes. In most cases, the whitening part is always located at the ejection part of the plastic part. In addition, if the mold temperature is too low and the flow channel is very narrow, the melt front temperature will drop rapidly and the curing layer will be thick. Once the curing layer has a large turn due to the part structure, it will be subjected to a large shear force. Pulling the curing layer in the high-temperature state will also lead to stress whitening.
- ② Solutions. After whitening, it can be improved by reducing the injection pressure, increasing the demolding slope, increasing the number or area of push rods, and reducing the surface roughness value of the die. In particular, chamfering should be prevented near the stiffener and boss. The ejection device of the demolding mechanism shall be set at the wall thickness of the plastic part or the thickness of the ejection part of the plastic part shall be appropriately increased. In addition, the surface finish of the cavity should be improved and the demolding stress should be reduced. Of course, spraying release agent is also a method, but attention should be paid not to have adverse effects on subsequent processes, such as hot stamping and coating.

(14) Crack

Cracking is a common defect of plastic products (Fig. 5.53). It includes filiform crack, micro crack, top white, crack on the surface of the part, and trauma caused by part die sticking and runner die sticking. According to the cracking time, it can be divided into demolding cracking and application cracking. The main reason is due to stress and deformation.

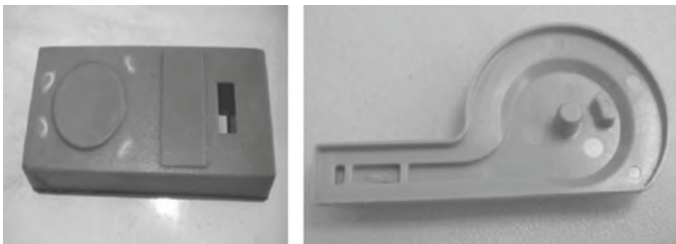


Fig. 5.52 Whitening

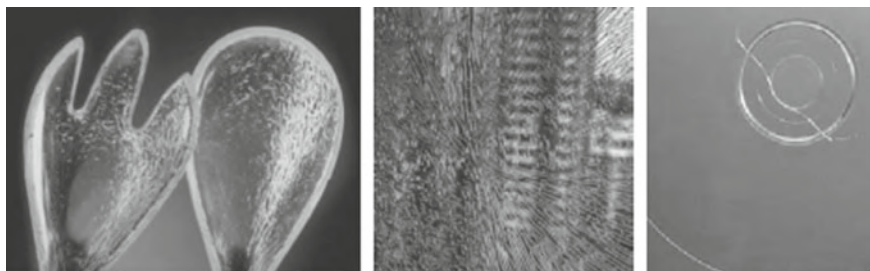


Fig. 5.53 Crack

- ① **Causes.** Cracking is mainly caused by residual stress, external stress and stress deformation caused by external environment. Some plastics are very sensitive to stress. After forming, they are not only easy to produce internal stress in the products, but also easy to embrittle and fracture under the action of large external force. The filling process of plastic melt in the mold is affected by flow shear stress and tensile stress, which makes the polymer macromolecules oriented, and there is no time to relax and form internal stress in the condensation process, so as to reduce the ability of plastic parts to bear external load. Non uniform orientation is often produced by inconsistent flow direction. The greater the degree of orientation, the greater the internal stress.

Material: if the humidity of the material is too high, the plastic will react with water vapor to reduce the strength and cause ejection cracking; Poor compatibility of mixed materials; The recycled material content is too high and the strength of the parts is low.

Mold: the ejection is unbalanced, resulting in the concentration of ejection residual stress and cracking; Unreasonable product design leads to local stress concentration; The product is too thin and the product structure design is unreasonable; When using metal inserts, the internal stress increases due to the different shrinkage between inserts and parts; Excessive release agent was used in the molding process.

Molding process: unreasonable adjustment of mold opening speed and pressure causes tensile effect on products, resulting in demolding cracking; The mold temperature is low, which makes it difficult to demold the product; Too high material temperature causes decomposition or welding marks; The injection pressure is too high, the speed is too fast, and the injection and pressure holding time is too long, resulting in excessive internal stress.

- ② **Solutions**

Materials: properly use release agent, and pay attention to often eliminate the aerosol and other substances attached to the mold surface; Fully dry the materials before forming; Pay attention to the selection of coatings and diluents that will not crack.

Molding process: avoid air entrainment due to poor feeding in the plasticizing stage; On the basis of increasing melt temperature and mold temperature and

ensuring melt flow, the injection pressure should be reduced as much as possible; Reduce the screw speed and injection speed, slow down the initial speed through the gate, and adopt multi-stage injection; Adjust the mold opening speed and pressure to avoid demolding cracking caused by rapid strong pulling products; Avoid cracking due to low mechanical strength caused by fusion marks and plastic degradation; Internal stress is eliminated and crack generation is reduced by annealing heat treatment immediately after forming.

If cracks have occurred on the surface of plastic parts, annealing can be considered to eliminate them. Annealing treatment is to fully heat the plastic part at a temperature about 5 °C lower than the thermal deformation temperature of the plastic part for about 1 h, and then cool it slowly. It is best to conduct annealing treatment immediately after forming the plastic part with cracks, which is conducive to eliminating cracks. However, there is residual stress in the crack, and the flux in the coating can easily develop the crack into a crack.

(15) Glass fiber steaks

The floating fiber is caused by the inconsistent fluidity of glass fiber and resin, the weak binding ability between resin and glass fiber and the exposure of glass fiber. The white glass fiber is exposed on the surface during the filling and flow of plastic melt. After condensation molding, a radial white trace is formed on the surface of plastic parts (see Fig. 5.54). When the plastic part is black, it will be more obvious due to the increase of color difference.

- ① Causes. In the process of plastic melt flow, due to the difference in fluidity and density between glass fiber and resin, the two have the trend of separation. The glass fiber with low density floats to the surface and the resin with high density sinks into the interior, resulting in the exposure of glass fiber. During the flow process, the plastic melt is subjected to the friction and shear action of screw, nozzle, runner and gate, which will not only cause local viscosity difference, but also destroy the interface layer on the surface of glass fiber. The smaller the melt viscosity, the more serious the damage to the interface layer, and the smaller the adhesion between glass fiber and resin. When the adhesion is small to a certain extent, glass fiber will get rid of the bondage of resin matrix, It will also cause gradual accumulation to the surface and exposure. In addition, the fountain effect

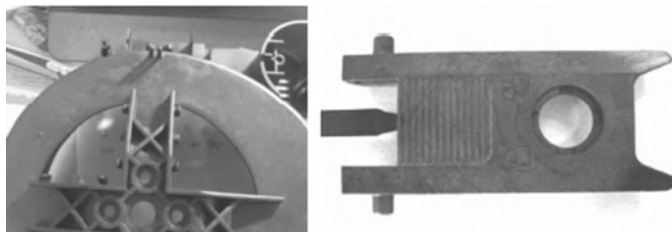


Fig. 5.54 Glass fiber steaks

will be formed when the plastic melt is injected into the cavity, that is, the glass fiber will flow from the inside to the outside and contact the surface of the cavity. Due to the low surface temperature of the mold cavity, the glass fiber with light weight and fast condensation is instantly frozen. If it cannot be fully surrounded by the melt in time, it will be exposed and form floating fiber.

Material: glass fiber is too long; Material viscosity is too high.

Mold: the gate is too small and the flow channel is too narrow; Improper gate position; The wall thickness of the product is designed unevenly.

Molding process: insufficient feeding amount; The injection pressure is too low;

The injection speed is too slow; The temperature of barrel, nozzle and die is low.

- ② Solutions. Floating fiber is a common defect in reinforcement modification. If the length of glass fiber can be controlled between 0.6 and 0.8 mm, floating fiber will not appear. However, due to the influence of glass fiber quality, resin viscosity, modification machine and process, mold and process, it is difficult to avoid floating fiber.

Materials: materials with low viscosity shall be selected as far as possible within the allowable range of mechanical properties; Short fiber or hollow glass beads shall be used as much as possible for glass fiber to make it have better fluidity and dispersion; For materials with high viscosity, some low viscosity resins and recycled materials can be added to increase fluidity.

Mold: reasonable mold structure design, appropriately increase the size of main flow channel, shunt channel and gate, and shorten the flow channel process; The gate can be thin, fan-shaped and annular, or multi gate to make the material flow chaotic, diffuse the glass fiber and reduce the orientation; Good exhaust function to avoid defects such as poor fusion, lack of material and burn.

Molding process: increasing back pressure helps to improve floating fiber phenomenon; When the injection speed is increased, the screw speed can be adjusted to 70–90%. Using a faster injection speed, the glass fiber reinforced plastic can quickly fill the mold cavity, which is conducive to increasing the dispersion of glass fiber and reducing the orientation; Higher injection pressure is conducive to filling, improve the dispersion of glass fiber and reduce the shrinkage of products; The whole screw retreats by 1–2 mm to prevent floating fiber in the gate; Graded injection molding is adopted for complex parts; Increasing the barrel temperature can reduce the melt viscosity, improve the fluidity, increase the glass fiber dispersion and reduce the orientation; Raise the mold temperature. At present, variable mold temperature technology is used to realize high mold temperature and rapid cooling, which can eliminate floating fiber; Reduce the screw speed to avoid damage to the glass fiber caused by excessive friction and shear force, damage the surface state of the glass fiber, and reduce the bonding strength between the glass fiber and the resin.

(16) Warpage

Warping deformation is due to improper forming conditions and mold design, which will lead to uneven shrinkage of plastic parts after demolding and generate internal

stress in the products. Such plastic parts will often produce warping deformation during use, resulting in product failure or dimensional error and assembly difficulty (Fig. 5.55).

① Causes

Material: material shrinkage is large.

Mold: the position distribution of mold cooling water path is uneven, and the temperature is not well controlled; On both sides of the product, the temperature difference between the cavity and the core is large; The designed product has uneven wall thickness, sudden change or too small wall thickness.

Molding process: the injection pressure is too high or the injection speed is too high; The barrel temperature and melt temperature are too high; The pressure holding time is too long or the cooling time is too short; It is ejected without sufficient cooling, which causes warpage and deformation due to the pressure of the ejector rod on the surface.

② Solutions

Warping deformation is one of the most serious quality defects of plastic parts, which should be solved mainly from the design of products and molds, and the effect of relying on the adjustment of forming process is very limited. The solution of warpage deformation is as follows.

Materials: select materials with small shrinkage.

Mold: try to make the product wall thickness uniform; The cooling system of the die is designed reasonably, so that the products can be cooled evenly and evenly; Control the temperature difference between the mold core and the mold wall; Reasonable determination of gate position and gate type can greatly reduce the deformation of products. Generally, multi-point gate can be used; The mold design is reasonable, determine the reasonable draft angle, ejector position and quantity, check and correct the mold core, and improve the strength and positioning accuracy of the mold; Improve the exhaust function of the die.

Molding process: reduce the injection pressure and injection speed, and adopt multi-stage injection to reduce the deformation caused by residual stress; Reduce the melt temperature and die temperature. If the melt temperature is high, the

Fig. 5.55 Warpage

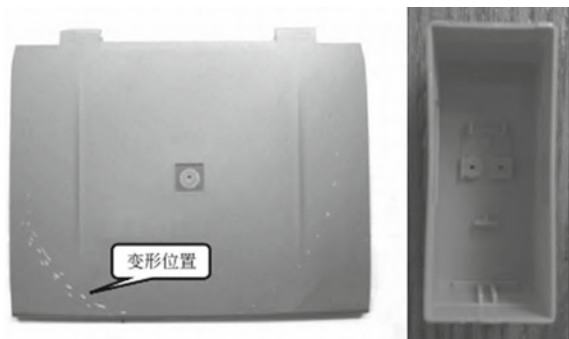




Fig. 5.56 Embrittlement

shrinkage of the product is small, but the warpage is large; otherwise, the shrinkage and warpage of the product are large; When the mold temperature is high, the shrinkage of the product is small, but the warpage is large. On the contrary, the shrinkage of the product is large and the warpage is small. Therefore, different schemes must be adopted according to different product structures. For slender plastic parts, the method of cooling after die fixing can be adopted; Adjust the cooling method or extend the cooling time to ensure uniform cooling of plastic parts; Set the screw back to reduce the compressive stress gradient and make the product flat.

(17) Embrittlement

Embrittlement is usually caused by internal stress after plastic degradation (Fig. 5.56). Too high temperature, too long time or chemical corrosion break the molecular chain, resulting in degradation and embrittlement of plastic products. Other materials, such as material pollution, too low mold temperature and weld marks, may cause embrittlement.

① Causes

Materials: impurities are mixed in raw materials, or other additives are improperly or excessively doped; The material is not dried, and the water vapor generated by heating reacts; The quality of plastics is poor, the number of regeneration is too many or the content of recycled materials is too high.

Mold: the product has sharp corners, notches or parts with great thickness difference that are prone to stress cracking; Unreasonable product design, too thin or hollow structure; The size of shunt channel and gate is too small; The products use metal inserts, resulting in large cold and heat specific capacity and large material brittleness; Abnormal injection cycle caused by poor mold structure.

Molding process: the injection speed and pressure are too small; Unreasonable mold temperature setting; Too high temperature makes it difficult to demold; Too low temperature causes premature cooling of products, which is easy to cause cracking; The temperature of barrel and nozzle is too low; High back pressure and rotating speed of screw pre molding cause material degradation; The strength decreases due to excessive residual stress or weld line.

Injection molding machine: there are dead corners or obstacles in the barrel to aggravate the degradation of molten material; The plasticizing capacity of the

machine is too small and the plastic plasticization is insufficient; The ejector device is unbalanced, the cross-sectional area of ejector rod is too small or improperly distributed.

- ② Solutions. For the embrittlement of products, it is necessary to find out the root cause of degradation and solve the problem. The improvement measures are as follows.

Materials: select materials with high strength and high molecular weight, and try not to use brittle materials or blend modified materials; Dry the material thoroughly.

Mold: the arrangement of shunt channel is balanced and reasonable, and the size of shunt channel is increased; The cooling system of the die is designed reasonably, so that the products can be cooled evenly and evenly; Set stiffeners on products; Improve the position of mold gate, improve gate design or add auxiliary gate; The mold design is reasonable, with exhaust slots and ear protectors in the welding part; Improve the exhaust function of the die.

Molding process: improve the injection speed and pressure, and adopt multi-stage injection to reduce the deformation caused by residual stress; Adjust the mold temperature to the appropriate value. Mold temperature is too high and demolding is difficult; If the mold temperature is too low, the plastic cools prematurely, the fusion of welding lines is poor, and it is easy to crack; Reduce or eliminate parallel connection and improve the quality of fusion line area; Reduce the back pressure of pre molding and screw speed to prevent material degradation due to shear overheating; Extend the injection time and pressure holding time.

(18) Residual stress

Residual stress refers to the sum of various residual stresses in the product without relaxation after molding. It is the phenomenon of surface warping and deformation due to residual stress in the injection molded part after demolding during polymer processing, especially injection molding (Fig. 5.57). The residual stress of injection molded products usually leads to warpage deformation and shape and size errors; At the same time, crazing and other defects caused by residual stress will make the components fail prematurely and affect their serviceability. Therefore, only when the residual stress is close to zero, the demolding is smooth and satisfactory products can be obtained.

It is generally believed that in the process of injection molding, the shear stress formed by the non isothermal flow of thin-walled plastic melt in the mold cavity is the main reason for the flow residual stress due to the lack of complete relaxation due to rapid cooling.

There are two sources of residual stress in injection molded products: orientation residual stress and shrinkage residual stress. For injection molding process, melt injection temperature, mold wall temperature, melt filling time and filling speed, holding pressure and the length of flow channel will affect the flow stress. The flow residual stress and thermal residual stress interact, and the thermal residual stress is one order of magnitude larger than the flow residual stress. Therefore, the influence of

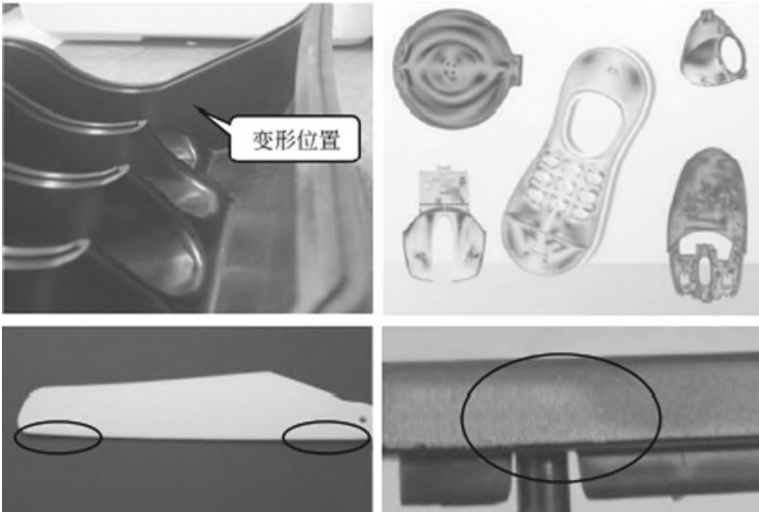


Fig. 5.57 Residual stress

thermal residual stress on injection molded parts is mainly considered in engineering. The generation mechanism of residual stress is shown in Fig. 5.58.

- a. Location of orientation residual stress.
- Gate position: it is easy to produce extrusion orientation stress due to fast shooting speed or long pressure holding time;
- Where the wall thickness changes sharply: the extrusion orientation stress will be generated due to the strong shear force at the thin wall position, especially from thick to thin;

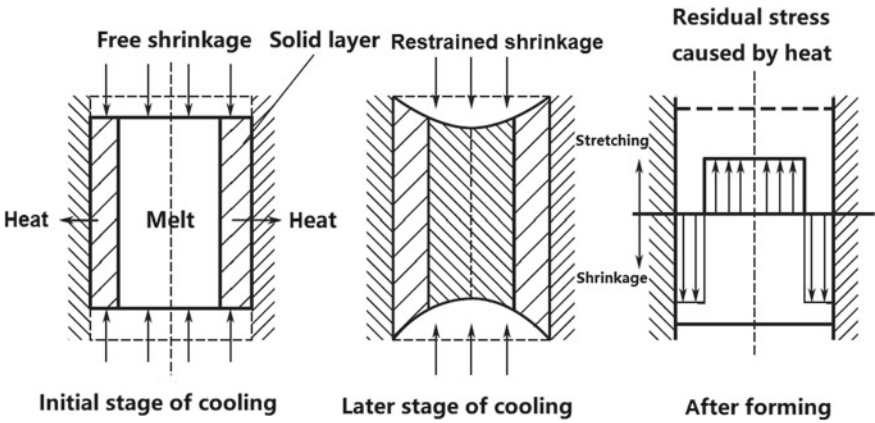


Fig. 5.58 Formation mechanism of residual stress

Material Flow Filling Imbalance: local extrusion will be caused by excessive filling, resulting in extrusion orientation stress.

- b. Location of shrinkage residual stress. It mainly occurs on products with uneven wall thickness, where the wall thickness changes sharply. Due to uneven heat dissipation, it is easy to produce different shrinkage orientations.

① Solutions

Mold: improper gate size and position setting will also lead to material flow filling imbalance, and local positions may be overfilled, resulting in large extrusion shear stress.

Molding process: on the premise of ensuring the injection speed, ensure a reasonable injection pressure to avoid stress caused by excessive local pressure; Long holding pressure and time will increase the molecular orientation at the gate and produce large residual stress; The mold temperature is too low, which will lead to the residual stress that cannot be released in time; Increasing the melt forming temperature will reduce the orientation stress of molecular chain due to reducing the viscosity, so as to reduce the residual stress.

Product structure: uneven wall thickness distribution. In the region of wall thickness change, the change of shear rate leads to the occurrence of stress; Stress concentration is easy to occur at sharp corners.

② Causes

Residual stress measurement methods can be divided into two categories: destructive measurement method (mechanical measurement method) and nondestructive measurement method (physical measurement method). For injection molded products, the typical residual stress methods include birefringence method, stripping method, drilling method and stress relaxation method. They have different testing mechanisms and their advantages and disadvantages. Among them, birefringence method belongs to nondestructive measurement method, while stripping method, drilling method and stress relaxation method belong to destructive measurement method. Among these methods, birefringence method and stripping method have been widely used.

Mold: the arrangement of shunt channel is balanced and reasonable, and the size of shunt channel is increased; The cooling system of the mold shall be designed and arranged reasonably to cure all parts of the workpiece surface at a uniform cooling rate as far as possible; The thickness of the die cavity is uniform to avoid large changes; Improve the gate position and gate design of the die to avoid too long process leading to different pressure transmission at different positions; Reasonable die design to avoid stress concentration caused by sharp corners.

Molding process: improve the injection speed and pressure, and adopt multi-stage injection to reduce the deformation caused by residual stress; Adjust the mold temperature to the appropriate value; Increase melt temperature; Properly reduce the holding pressure and holding time to avoid gate stress concentration.

Heat treatment: raise the temperature so that it can make the molecular chain of plastic parts move, and let the frozen molecular chain relax after heating to produce disorder, so as to eliminate the residual stress. Methods include oven heat treatment and far infrared heating treatment.

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Chapter 6

The Future of Polymer 3D Copying Technology



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Composite 3D photocopying technology (i.e. molding and forming technology) is widely used in industrial production, including injection molding, blow molding, extrusion, die-casting or forging, smelting, stamping and other processing methods. More than 5% of metal products (including semi-finished products) and more than 95% of plastic products are formed by molds (including rolling rollers) [1]. The production capacity of molds in a country directly determines the development of 3D copying technology. The most important development direction of 3D copying technology in hardware is the rapid intelligent manufacturing of molds.

Intelligence has always been an important trend of future development. With the proposal and development of the concept of Intelligent Internet of Things and Industry 4.0, the intelligent revolution of 3D copying technology will also take place.

6.1 Smart Manufacturing of Molds

The essence of 3D copying technology is molding, and molds are the core component of 3D copying technology. Traditional mold manufacturing often has long processing cycle, difficult mold manufacturing and high price, which makes it difficult to enter public life like 3D printer. The rapid manufacturing of mold is particularly important. At the beginning, people called it rapid economic molding, which is the traditional fast mold technology, and emphasized its low price.

There are many methods of traditional mold manufacturing, such as CNC milling, form grinding, EDM, WEDM, casting mold, ECM, electroforming, pressure machining and photo etching. The traditional rapid mold (such as low melting point alloy mold, electric casting mold, spray mold, etc.) is difficult to fully meet the requirements of users because of its rough process, low precision and short service life. Even the traditional rapid mold often cannot achieve the real “rapid” because of the problems in mold design and manufacturing.

As science and technology continuous to evolve, these shortcomings of mold manufacturing are constantly being overcome, for example, with the rise of 3D printing molds based on 3D printing technology, and adaptive molds inspired by “movable type”. These technologies will continue to evolve and mature in the near future.

6.1.1 3D Printing of Molds

Mold industry is a very large span industry, which is related to all fields of manufacturing industry. In the modern world, manufacturing and molding are highly interdependent, and the parts of countless products are manufactured either by molding (injection, blow molding and silicone) or by casting (investment, foundry and spinning). No matter what application, mold manufacturing can improve efficiency and profit while ensuring quality. CNC machining is the most commonly used technology in mold manufacturing, as shown in Fig. 6.1. While it can provide highly reliable results, it is also very expensive and time-consuming. So many mold manufacturing enterprises are also looking for more effective alternatives. But through additive manufacturing (ALM, or 3D Printing) is a very attractive method to make molds, because molds are generally small batch production and the shape is more complex, which is suitable for 3D printing.

Nowadays, 3D printing and various printing materials (plastic, rubber, composite, metal, wax, sand) have brought great convenience to many industries, such as automobile, aerospace, medical and so on. Many enterprises have integrated 3D printing in their supply chain, including mold manufacturing (see Fig. 6.2).

(1) Advantages of 3D printing mold manufacturing

- ① Shorten the mold production cycle 3D printing molds shorten the entire product development cycle and become the source that drives innovation. In the past,

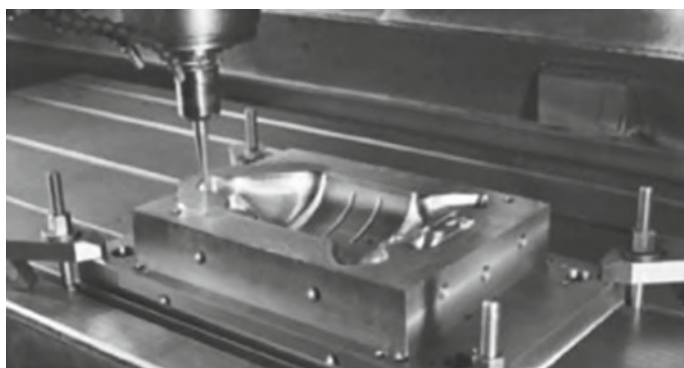


Fig. 6.1 CNC machining die

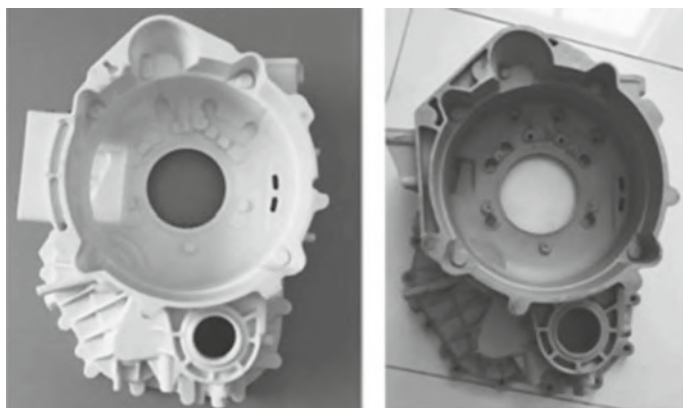


Fig. 6.2 3D printed wax mold of clutch housing (left) and metal part obtained after precision casting (right)

considering that a large amount of money was needed to make new molds, companies sometimes chose to postpone or abandon the design update of products. By reducing the mold production preparation time, and making the existing design tools can be quickly updated, 3D printing enables enterprises to afford more frequent mold replacement and improvement. It can make the mold design cycle keep up with the pace of product design cycle.

In addition, some companies have purchased their own 3D printing equipment to manufacture molds, which further accelerates the speed of product development and improves flexibility and adaptability. Strategically, it increases the ability of the supply chain to protect against the risks of extended deadlines and stalled development, such as obtaining inappropriate molds from suppliers.

- ② **Manufacturing cost reduction** If the current cost of metal 3D printing is higher than that of traditional metal manufacturing process, then the cost reduction is easier to achieve in the field of plastic products.

Metal 3D printing mold has an economic advantage in the production of some small, discontinuous series of end products (because the fixed cost of these products is difficult to amortization), or for some specific geometric shapes (specially optimized for 3D printing), especially when the materials used are very expensive and the traditional mold manufacturing leads to a high material scrap rate, 3D printing has the advantage of cost.

In addition, the ability of 3D printing to produce accurate molds in a matter of hours will also have a positive impact on the manufacturing process and profits, especially when production is down or mold inventory is very expensive.

Finally, it is often the case that the mold needs to be modified after production has started. The flexibility of 3D printing enables engineers to try countless iterations at the same time and reduce the upfront cost caused by mold design modification.

- ③ The improvement of mold design adds more functionality to the end product. In general, the special metallurgical method of metal 3D printing can improve the metal microstructure and produce fully dense printing parts. Compared with those forged or cast materials (depending on heat treatment and testing direction), the mechanical and physical properties are the same or better. Additive manufacturing brings more choices for engineers to improve the design of molds. When the target part is composed of several sub parts, 3D printing has the ability to integrate design and reduce the number of parts. This simplifies the assembly process and reduces tolerances.

In addition, it can integrate complex product functions to make high functional end products faster and have fewer product defects. For example, the overall quality of an injection molded part is affected by the heat transfer between the injection material and the cooling fluid flowing through the fixture. If manufactured with conventional technology, the channel leading to the cooling material is usually straight, resulting in a slow and uneven cooling effect in the molded parts. 3D printing can achieve any shape of cooling channel to ensure the cooling with shape, which is more optimized and uniform, and ultimately leads to higher quality parts and lower scrap rate (see Fig. 6.3). In addition, faster heat removal significantly reduces the injection cycle, as the cooling time can generally account for up to 70% of the whole injection cycle.

- ④ Optimizing tools and improving minimum performance 3D printing reduces the threshold of verifying new tools, which can solve the needs that cannot be met in the manufacturing process, so that more mobile fixtures and fixed fixtures can be invested in manufacturing. Traditionally, due to the considerable cost and effort required to redesign and manufacture them, the design of tools and corresponding devices are always used for as long as possible. With the application of 3D printing technology, the enterprise can at any time for any tools for renovation, but is not limited to those who have been scrapped and is not in conformity with the requirements of the tool.

Due to the need for a small time and initial cost, 3D printing makes it more economical to optimize the tools to achieve better marginal performance. So technicians can consider ergonomics more in design to improve their operation comfort, reduce processing time, and make it easier to use and store. Although this may only reduce the assembly operation time by a few seconds, it can't stand that a little makes a lot. In addition, optimizing tool design can also reduce the scrap rate of parts.

- ⑤ Custom molds help to achieve the customization of the final product. Shorter production cycle, more complex geometry and the ability to reduce the final manufacturing cost enable enterprises to manufacture a large number of personalized tools to support the manufacturing of customized parts. 3D printing mold is very conducive to customized production, such as medical equipment and medical industry. It is able to provide the surgeon personalized 3D printing

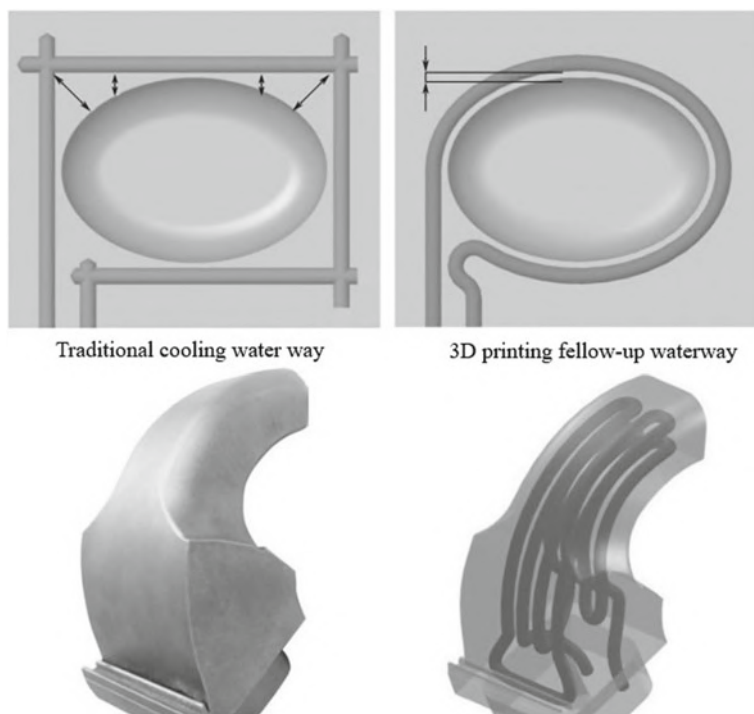


Fig. 6.3 3D printing metal follow-up and special-shaped waterway molds

equipment, such as surgical guide and tools that enable them to improve the operation effect and reduce the operation time.

Here are several rapid mold manufacturing techniques based on 3D printing [2].

(2) Direct 3D manufacturing technology of high-performance metal mold

The direct 3D manufacturing technology of high-performance metal mold has been the focus of attention due to its advanced technology. Metal powder Selective Laser Sintering (SLS) is the most widely used process. With the aid of computer aided design and manufacturing, it uses the thermal effect of high-energy laser beam to soften or melt one layer of material, and then it is bonded and stacked layer by layer to obtain three-dimensional solid parts. As early as in 1898, EOS company of Germany introduced the technology of directly using SLS process to form any complicated high-precision steel mold manufacturing technology, which no longer needs secondary sintering molding, metal penetration and other cumbersome processes. Its molded parts can be directly used as injection molds for mass production.

Laser Engineered Net Shaping (LENS) technology developed in the United States is an important representative of the technology. LENS process is a kind of process that can directly manufacture metal mold from CAD solid model. In this process,

the Nd: YAG laser beam is focused on the surface of molten pool formed by metal powder injection, and the whole device is protected by inert gas. By laser beam scanning movement, causes the metal powder materials piled up one by one, eventually forming a complex shape of the mold. Beijing University of Aeronautics and Astronautics has recently made a breakthrough in the direct manufacturing of large metal parts of titanium alloy, which is a landmark achievement in the development of 3D printing technology in China. At present, the research team focuses on the manufacturing of high strength steel metal parts, and it also has some advantages. It is expected to be used in direct 3D manufacturing of high-performance metal mold.

With the continuous maturity and application of 3D printing and rapid tooling technology, we must pay attention to the following three issues:

- ① Material processing equipment is directly related to the quality of finished products. High power laser and other components are the key equipment for material preparation. At present, they are basically imported, which is also the technical difficulty we should focus on in the future.
- ② The preparation of high-performance metal powder based on 3D printing is very important for 3D printing metal mold manufacturing technology, and it is a new hot spot in the industry.
- ③ The material performance of finished products is the final standard to consider the advanced level of direct manufacturing technology of high-performance metal components. Fatigue strength, fatigue crack propagation rate and other properties need to meet the application standards, which is also the key point that we need to make further breakthroughs in the future.

Other similar technologies are as follows.

Shape Deposition Manufacturing (SDM) process is used to manufacture the multi-component metal injection mold with complex inner flow channel. After a certain post-treatment, the dimensional accuracy and surface finish of the mold meet the requirements. Because this kind of injection mold contains the inner channel which other methods can't do, the cooling effect is satisfactory, therefore, people pay attention to it.

Another example is metal deposition rapid tooling combined with High Speed Milling (HSM). Although the development of high-speed milling equipment and technology has formed competition for 3D printing rapid mold technology, this is particularly obvious at the end of the twentieth century, HSM cannot complete more complex shape (such as the mold with cooling inner channel), nor can it manufacture the mold with functional gradient and material gradient, which can only be the cutting of the same material. Actually, high-tech can be complementary to each other. Recently, with the assembly mold, people adopt different rapid manufacturing methods for different components, resulting in the resultant effect. Many rapid tooling companies use 3D printing and HSM technology at the same time, which makes use of their complementary characteristics. From the fundamental direction of the

development of manufacturing science, discrete/stacked forming is bound to replace strip forming in many aspects, and 3D printing will occupy its place.

(3) Rapid mold technology for unbaked ceramic type precision casting

This technology belongs to indirect 3D printing rapid mold technology, the key is the manufacturing of precision ceramic mold.

The basic principle of precision ceramic mold manufacturing is that the refractory with high fire resistance and low thermal expansion coefficient is used as aggregate, and the hydrolysate is used as adhesive to prepare ceramic slurry. Under the action of catalyst, the ceramic mold with smooth surface and high dimensional accuracy is made through a series of processes such as grouting, gelling, hardening, stripping, spray firing and roasting, which are used to cast various precision castings. It is suitable for the production of various metal rapid tooling.

The application of precision ceramic mold manufacturing technology in metal mold manufacturing has the following obvious advantages: No special equipment, less investment; The production cycle is short, and the finished product can be obtained within 2–3 days after the master mold is available; Compared with the machining mold, the cost of precision ceramic mold can be reduced several times to dozens of times; The material has high fire resistance and can be used to cast various alloy, cast iron and carbon steel castings; Excellent reproductivity: high dimensional accuracy and surface finish of castings; It can be used to cast large precision castings.

High-temperature roasting of ceramic types will produce cracks, deformation and other problems that affect the precision of ceramic mold casting; for large ceramic mold, the scale of baking furnace and the uniformity of temperature field in the furnace are also difficult to solve. Non-roasting precision ceramic type manufacturing technology is developed on the basis of precision ceramic mold manufacturing technology aiming at various problems in the process of baking. The non-baking precision ceramic mold manufacturing technology can overcome the problems of cracks and deformation caused by high temperature baking of ceramic mold, and can greatly improve the precision of casting; At the same time, due to the use of non-baking technology, there is no need to build a roasting furnace, which is of great significance for large castings. This can not only save the cost of building a large roasting furnace, but also save a lot of power resources, thus greatly reducing the cost of castings.

The non-baking precision ceramic mold manufacturing technology has a broad application prospect in the manufacturing field of large metal mold. Although the principle of non-baking precision is simple, the practical operation is difficult, and the range of process parameters can be changed is narrow, which affects the popularization of the technology and should be paid full attention to.

(4) SLS manufacturing of wax mold and sand molds for casting

Selected Laser Sintering technology (SLS) has been developed to obtain that 3D solid metal parts can be used for the rapid direct manufacturing of metal mold. If other materials are used, they can be used for the rapid and indirect manufacturing of metal mold.

SLS technology has a wide range of forming materials, which are suitable for a variety of powder materials, except metal, such as polymer, ceramic and coated sand powder. Compared with the traditional process, SLS technology can form investment mold or sand mold (core) with higher complexity and strength in a shorter manufacturing cycle, shorten the development cycle of new products and reduce the development cost.

The rapid casting technology based on SLS is characterized by simplicity, accuracy, reliability and ductility, which can be effectively applied to the rapid manufacturing of engine prototype in the design and development stage; It is suitable for single piece, small batch trial production and production, can respond to the market quickly and provide small batch products for testing and testing, which helps to ensure the product development speed; The controllability of the forming process can be modified immediately at low cost in the design and development stage, so as to check the design or provide the assembly model, which is helpful to improve the product development quality; The diversity of raw materials provides different process combinations for product development the localization of raw materials and the combination of forming process with traditional process are helpful to reduce the development cost; The combination technology is quick and supports the improvement of product renewal frequency, which helps to promote the product to enter the market as soon as possible.

The similar technology is to use various 3D printing forming machines to make product samples first, and then turn over the mold, which is a time-saving and cost-effective method. In aviation and other fields, many key parts are difficult to be machined by traditional machining methods, and must be formed by mold. For example, for a pump body part, the traditional mold opening time is 8 months, and the cost is at least 30 million yuan. If the product design is wrong, the whole set of molds will be discarded. The polymer sample was made for the product with SLS, which was used as the master mold to turn the silicone mold. Fix the master mold in the aluminum standard mold frame, pour in the prepared silicone rubber, stand for 12–20 h, the silicone rubber is completely cured, open the mold frame, take out the silicone rubber, cut along the predetermined parting line with a knife, take out the master mold, and the silicone mold used for casting the pump shell wax mold is turned over successfully. After coating, baking, wax loss, pressure casting and sand blasting, a qualified pump shell casting can be manufactured in just two months. After necessary machining, it can be installed and operated. Compared with the traditional method, the whole trial production cycle is shortened by 2/3 and the cost is saved by 3/4.

(5) Rapid manufacturing of medium hard mold and soft mold based on Internet

The 3D printing prototype is used as the master mold, and soft materials such as wax, silicone rubber, epoxy resin and polyurethane were poured to form the soft mold. These soft molds can be used as injection molds for trial production and small batch production, or as intermediate transition molds and low melting point alloy casting molds for hard molds. These soft molds have good elasticity, reproductivity and certain strength, which can greatly simplify the structure design of

the mold and facilitate demolding when pouring complex molds. For example, the compressive strength of TEK high temperature vulcanized silicone rubber can reach 12.4–62.1 MPa, the working temperature is 150–500 °C, and the mold life is generally 200–500 pieces; Generally speaking, the service life of the soft mold made of room temperature cured silicone rubber is 1025 pieces, and that of the soft mold made of epoxy resin is 300 pieces. For another example, DuPont has developed a kind of light cured resin working at high temperature, which can directly form the mold by Stereo Lithography (SL) process. It is used in the injection molding process, and its service life can reach more than 22 pieces.

The metal powder coated with adhesive can be directly sintered by SLS process and narrow 3D printing (3D-P) process, or the metal sheet coated with adhesive can be directly cut by LOM process. After the model is manufactured, the adhesive is removed by heating, and the low melting point metal is infiltrated into the model to produce the metal composite mold with medium hardness, which can be used in mass production. At present, the metal composite mold with complex shape has been manufactured. In addition, zinc base alloy is a kind of medium melting point alloy, which also has medium hardness. The hardness of low melting point alloy (Bi-Sn alloy) is lower, but it can be classified as medium hardness. They can use the traditional mature rapid tooling technology. In recent years, some people have combined them with 3D printing technology and introduced some composite processes, which not only improves the precision of the mold, but also accelerates the design and manufacturing cycle of the mold.

In addition, the traditional spray mold (including arc spraying, plasma spraying, etc.), electroforming mold, silicone mold, electrochemical machining mold, etc., in the manufacturing of master mold or prototype, more widely used 3D printing technology, they are no longer the traditional sense of rapid mold, should also be classified as rapid mold technology based on 3D printing.

(6) Network manufacturing technology of rapid tooling based on Internet

The information superhighway marked by the Internet is mainly used to organize manufacturing resources flexibly and rapidly. The existing 3D printing equipment resources, intellectual resources and various core capabilities scattered in different regions are quickly combined into a kind of business entity network alliance enterprise without walls, beyond space constraints, connected by electronic means and under unified command, so as to rapidly launch high-quality, high-quality, high-quality, high-quality, high-quality, high-quality, high-quality, high-quality, high-quality printing products Low cost 3D printing prototype, mold and new products are urgently needed in modern manufacturing industry.

For example, the manufacturing of automobile panel mold has high requirements for its rapidity. China has begun to organize networked manufacturing alliance for panel molds, which is a collaborative network formed by enterprises or organizations distributed all over the country for the common goal. The related information of panel and its mold is the basis of the collaboration of the whole networked manufacturing alliance. The purpose of information modeling is to establish a unified product model that can be understood and processed by computer, which can be used to organize,

manage and control the process of product design and manufacturing in networked alliance, and realize the effective sharing of information. This is of great significance for the timely launch of new models. At present, various rapid tooling technologies based on 3D printing are being applied in many large and medium-sized automobile enterprises, and the related networked manufacturing has been mentioned on the agenda.

According to the characteristics of 3D printing manufacturing technology, this technology is very suitable for manufacturing mechanical parts with complex shape and structure and complex material composition, including large and medium-sized parts and even micro parts. Therefore, it can complement the rapid tooling manufacturing technology. At present, 3D printing technology has developed to a new stage. It can not only directly manufacture metal parts, but also can meet the requirements of forming precision, but also play a great role in the manufacturing of forming parts with very large size and micro nano size. It is also very attractive for the rapid mold with wide size distribution, strict precision requirements and short design and manufacturing cycle. 3D printing can play an irreplaceable role in many fields, and has been more and more widely used. Rapid tooling technology based on 3D printing should be paid more attention.

In a word, the full application of 3D printing technology in the field of product and mold design and manufacturing, especially in rapid mold technology, can significantly shorten the product launch cycle, reduce costs, improve quality and enhance the competitiveness of enterprises. To speed up the research of this technology and really serve the economic construction of our country, it is bound to achieve good social and economic benefits.

Figure 6.4 shows the 3D printing plastic injection mold exhibited by boy company in K2016. For injection molded products, manufacturers often need to produce small quantities of injection molded parts for further product verification before the products are formally put into mass injection production. In this case, if we use metal injection mold to produce small batch of injection parts, it will produce high cost and wait for a long metal mold manufacturing cycle. However, with the continuous maturity of 3D printing technology, small batch injection molding with 3D printing plastic mold can solve these problems.

Although 3D printing plastic injection mold saves time and cost compared with metal mold, the temperature of polymer melt is higher in the process of injection molding. Only uniform and rapid cooling after injection can ensure the quality of plastic products. It requires the mold to have good thermal conductivity, and it is not difficult to imagine that the thermal conductivity of plastic cannot be compared with that of metal. The thermal conductivity of plastic mold is weak, and the injection cycle becomes longer. Therefore, 3D printing plastic mold is more suitable for the production of a small number of new products in the research and development stage, or a small number of urgent products and small and medium-sized injection molding products.

Fig. 6.4 3D printing plastic injection mold displayed by BOY company in K2016



6.1.2 Adaptive Molds

For the rapid manufacturing of molds, inspired by “movable type printing”, the author puts forward the concept of self-adaptive assembly mold. Including adaptive injection mold, adaptive suction mold, adaptive blow mold and so on.

Traditional molds often have a mold that can only mold one type of product, just like engraving printing, every work must be engraved into a plate. The concept of self-adaptive mold is to design the mold as a kind of unit column combined mold which can change with the shape of the product. Mold unitized, according to the outline of the molded products to re assemble, get the corresponding mold, to adapt to the needs of different products.

(1) Adaptive injection mold

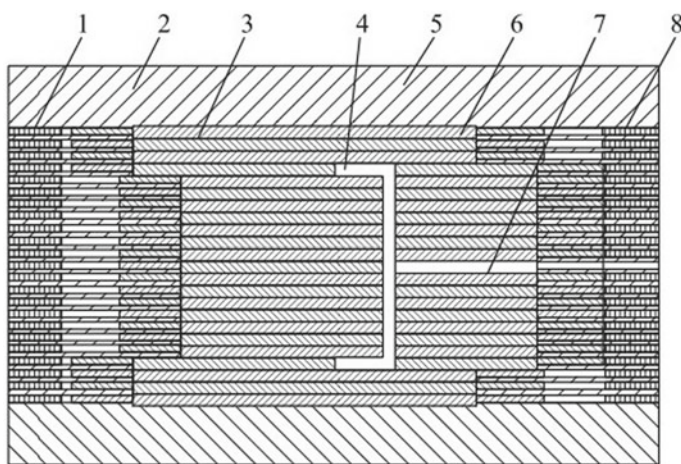
The patent “A Method of 3D Copy of Technology and Equipment” refers to a kind of adaptive injection mold. Through the differential unit of the injection mold, redistribution and combination, the mold suitable for the product is formed, and the adaptive matching of the mold to the three-dimensional entity is realized. The specific method is to scan three-dimensional solid or use three-dimensional software to model directly, and then use computer programming language to process the three-dimensional model as a unit, and then control each differential unit module of the mold to form the mold cavity of the corresponding product, and then realize the rapid and efficient copying of 3D solid by injection molding.

The core device is the unit combined mold device, as shown in Fig. 6.5. It is composed of moving mold base plate, moving mold electromagnet system, fixed plate around moving mold, moving mold unit module, fixed plate around fixed mold, fixed mold unit module, fixed mold electromagnet system, fixed mold base plate, etc. The moving model unit module and the fixed model unit module can move

linearly under the action of the moving model electromagnet system and the fixed model electromagnet system respectively. The structure of the moving mold unit module is the same as that of the fixed mold unit module, which is composed of unit bar, permanent magnet iron bar and graphene coating. The unit rod is connected with the permanent magnet rod up and down, and the periphery of the unit rod is covered with graphene coating. By changing the direction of the current in the electromagnet, it can attract and repel the permanent magnet iron rod. By changing the size of the current in the electromagnet, it can adjust the distance from the end of the permanent magnet iron rod. The size and direction of the current in the electromagnet are controlled by the computer program to make the unit bar and the permanent magnet bar move accurately. The mold cavity and gate are formed by the position coordination of the moving mold unit module and the fixed mold unit module, and then the three-dimensional products are obtained by injection molding.

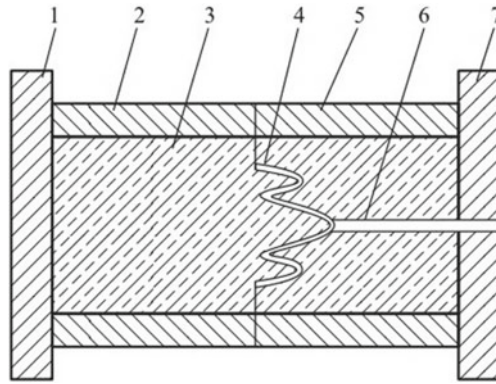
The patent also mentions a method to form a mold cavity by changing the internal magnetic field of the magnetic fluid to control the shape of the magnetic fluid, as shown in Fig. 6.6.

Magnetic fluid, also known as magnetic fluid, ferromagnetic fluid or magnetic fluid, is a new type of functional material. It not only has the fluidity of liquid, but also has the magnetism of solid magnetic materials. It is a kind of stable colloidal liquid which is composed of magnetic solid particles with nanometer diameter (less than 10 nm), base carrier liquid (also called media) and surfactant. The fluid has no magnetic attraction in static state, but shows magnetism only when the magnetic field is applied, and reacts, and its shape changes with the magnetic field.



1- Electromagnet system in moving mold; 2-Fixed plate around moving mold; 3- Unit block of moving mold; 4- Mold cavity; 5- Fixed plate around static mold; 6- Unit block of static mold; 7- Gate; 8- Electromagnet system in static mold

Fig. 6.5 Unit combined mold device



1- Moving platen; 2-Fixed plate around moving mold; 3- Magnetic fluid; 4- Mold cavity;
5 - Fixed plate around static mold; 6- Gate; 7- static platen

Fig. 6.6 Magnetic fluid adaptive mold

This method can form complex cavity and form complex products, which is suitable for small cavity pressure situation.

(2) Self adaptive blister molds

The patent “Personalized Mask Rapid Manufacturing 3D Printing and Copying All-in-One Machine” [3] refers to an adaptive blister mold, as shown in Fig. 6.7. Its core lies in the digital control of 3D blister mold. The digital control 3D blister mold includes unit column, unit column support plate, return spring, electromagnetic displacement generator, vacuum channel and mold box; The return spring is set in the lower part of the unit column to realize the automatic reset function; There is a magnet at the lower end of each unit column, and the polarity of the magnet is related to the electromagnetic generator below; There are magnets at the lower end of each unit column. The polarity of the magnet is the same as that of the magnetic field produced by the electromagnetic generator below. The same-sex magnetic poles are mutually exclusive to realize the movement of the unit column up and down. The electromagnetic displacement generator is set at the front and bottom of the unit column, so that the force on the unit column is relatively uniform and stable. The vacuum channel is set in the center of the bottom of the mold box, The unit column center has air holes or a vent passage between the unit columns. The unit column support plate is the mounting plate of the unit column. The number of holes in the support plate of the unit column is the same as that of the unit column. The unit column support plate is guided by the unit column. The upper section diameter of the unit column is larger than the section diameter of the mounting hole of the unit column on the unit column support plate. The spring is on the single column. Under the support plate, the unit column support plate is located in the mold box near the middle position, and the single column can move up and down freely in the air of the support plate under the action of spring and electromagnetic force.

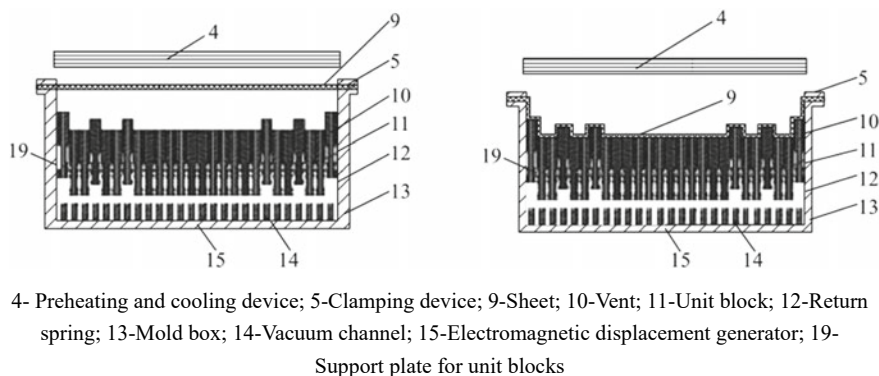


Fig. 6.7 Adaptive blister mold (left: before forming; right: after forming)

The working principle of the digital control 3D plastic suction mold is to control by computer control system, so that the coil in the electromagnetic displacement generator can generate different current values, thus forming different electromagnetic forces of different sizes. And then, according to the principle of magnetic field repelling each other with the same pole, the unit column moves up and down to achieve different displacements, forming different mold surfaces, realizing the variability of the mold.

The self-adaptive blow mold is basically the same as the self-adaptive suction mold, but the difference is whether to inhale or blow.

Although adaptive die is only a concept at present, it is only seen in patents. However, with the continuous development of manufacturing industry, it provides a possibility for rapid mold manufacturing and personalized 3D copying technology

6.2 3D Pressing Technology

Aiming at the forming of foamed sheet and fiber prepreg sheet, the author puts forward the concept of “3D printing forming”. Polymer 3D printing technology, also known as polymer 3D pressing ironing technology, also belongs to the category of 3D copying technology in essence. It refers to the technology of one or more points hot pressing of polymer sheet, so as to realize the rapid and efficient reproduction of sheet products.

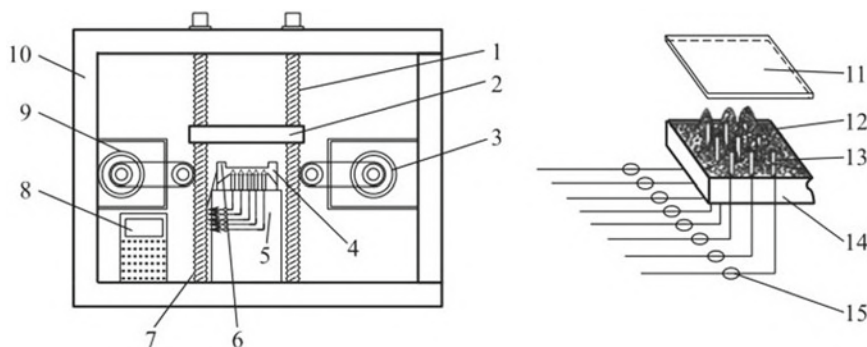
The patent “Thermal Magnetic Multi Field Coupling Electric Control Magnetic Fluid Compression Molding 3D Printing Device and Method” [4] proposes a 3D printing embossed wallpaper method for foamed materials, as shown in Fig. 6.8. Its working principle is to use specific magnetic field to control the wave crest of magnetic fluid, and then to carry out thermoplastic carving on foaming materials. Because the shape of the magnetic fluid changes with the change of the magnetic

field, the control system can send out a specific magnetic field to get the desired shape of the magnetic fluid, and the foam material can be multi-point pressed.

It mainly includes the following steps: in the first step, the conveying system transports the foaming material to the guide rail directly above the magnetic fluid through the conveyor belt, and the pressing plate fixes it; In the second step, the temperature control system controls the electromagnetic heater to heat the magnetic fluid, which is adjusted by the temperature sensor to achieve the optimal thermoforming temperature of the foaming material; In the third step, the control system analyzes the three-dimensional model of the pattern, and then controls the corresponding pulse electrode of each plotter to generate voltage to adjust the height of the generated MHD peak; In the fourth step, due to the voltage generated by the pulse electrode and the unique magnetization of the plotter, the magnetic fluid in the printing system forms a state with the plotter as the center and holding the wave crest protrusion, so as to thermoplastic the foaming material; The fifth step is to transport the thermoplastic 3D relief wallpaper to the conveyor belt.

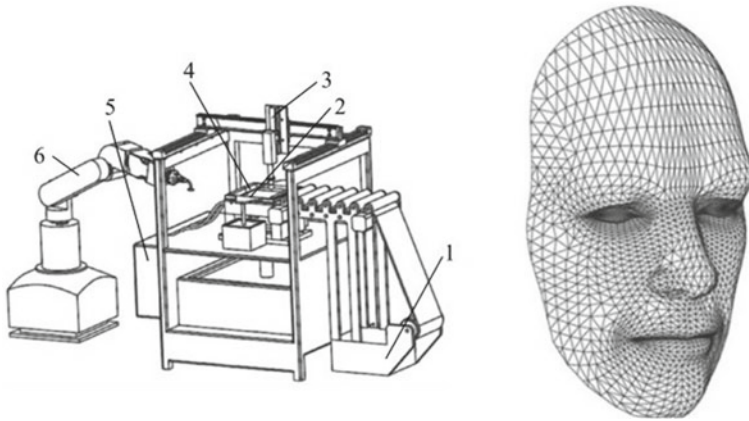
The patent “Manipulator Controlled Magnetic Fluid Press Molding Device and Method” [5] refers to a 3D pressing molding device to realize the forming of fiber prepreg sheet. The single-mode system can be used to complete the forming of fiber prepreg material, as shown in Fig. 6.9. On the left is the schematic diagram of 3D pressing molding device, and on the right is the press molding face model.

At the beginning of processing, the unwinding roller of the feeding preheating device unfolds and unwinds the fiber prepreg, the conveying motor drives the conveying roller to transport the curled fiber prepreg, and the fiber prepreg is preheated by the preheating roller and then enters the single mode; At this time, the conveying stops and the shearing and pressing device moves down to cut and



1-Ball screw; 2-Pressing plate; 3-Motor; 4-Magnetic fluid vessel; 5-Permanent magnet; 6-Transportable guide rail; 7-Control line; 8-Control system; 9-Conveying belt; 10-Frame; 11-Foaming material; 12-Magnetic fluid; 13-Description meter; 14-Permanent magnet; 15-Pulse electrode

Fig. 6.8 Thermal- mechanical-magnetic multi field coupling 3D pressing device (left) and its schematic diagram (right)



1-Feeding and preheating unit; 2-Clamping unit; 3-Pressing unit; 4-Half mold; 5-Mold heating unit; 6- Pick up manipulator

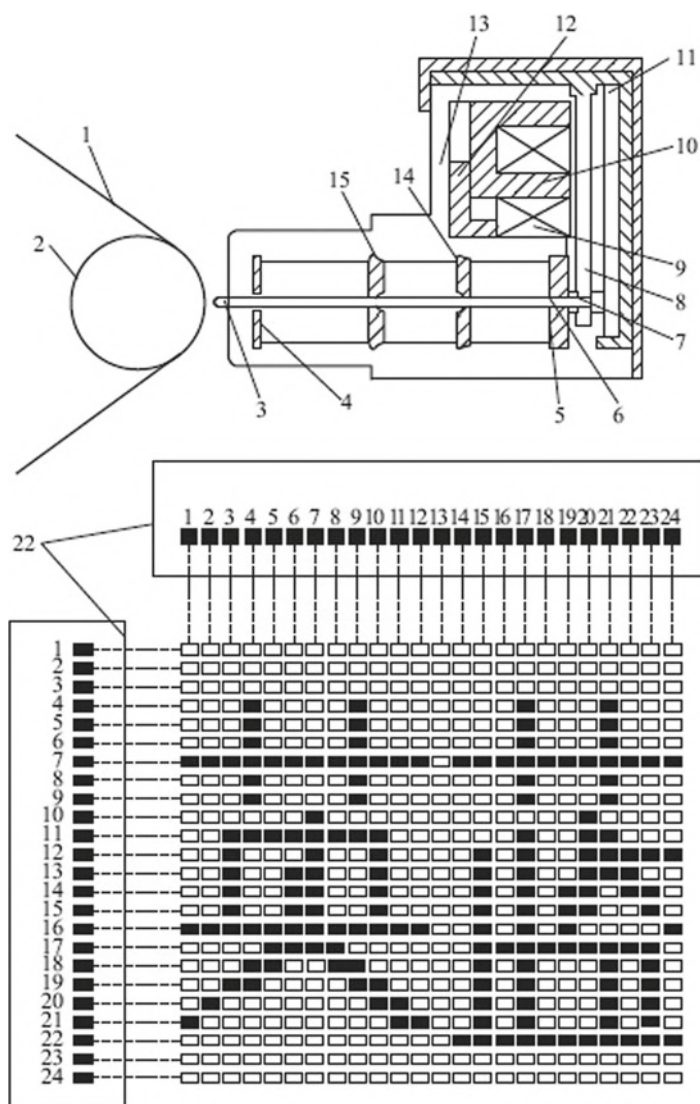
Fig. 6.9 Manipulator controlled magnetic fluid 3D pressing device (left) and its products (right)

press the fiber prepreg; Then the pressing device presses and irons the product, and the ejecting mechanism ejects the product after forming; Finally, the manipulator takes out the product and carries on the next cycle.

The core component of the invention is a pressing device. The pressing head of the pressing device can realize three axial movement on the guide rail with three degrees of freedom, and fully press the material. There is an electromagnet inside the ironing head, which can generate a magnetic field in the magnetic fluid after power on, and make the shape of the magnetic fluid change with the change of the set magnetic field. An electric heating rod is installed inside the pressing head to heat the magnetic fluid.

The patent “Embossed Mural Digital Lattice Hot Pressing 3D Printing Forming Method and Device” [6] proposes a method of using heated special printing head to strike foaming material to form three-dimensional pattern, as shown in Fig. 6.10. The basic method is to drive a number of print heads to form a digital dot matrix through the control system, and to carry out 3D printing with “plane” as the unit.

It mainly includes the following steps: the first step is to heat the special print head by the electromagnetic heater and adjust it by the temperature sensor to achieve the required plasticizing and melting temperature of the material; In the second step, the control system controls the excitation coil to be powered on for trial printing. The pressure sensor feeds back the printed depth and force to the control system. The control system adjusts the current of the excitation coil to achieve the required groove depth of the printed pattern; In the third step, the drum or conveyor belt transports the foaming material to the special printing head to enter the formal printing stage; In the fourth step, the control system controls the multi needle printing from the three-dimensional model of the pattern, and forms the digital dot matrix printing pattern on the foaming material.



1-Foaming material; 2-Roller or conveying belt; 3-Specific pressing heat; 4-Needle guide piece 1; 5-Spring piezo resistive sheet; 6-Return spring; 7-Compression spring block; 8-Armature; 9-Excitation coil; 10-Electromagnetic core; 11-Permanent magnet; 12-Position baffle; 13-Pressing heat shell; 14-Needle guide piece 2; 15- Needle guide piece 3; 16-Control system

Fig. 6.10 Digital dot matrix 3D pressing device

6.3 The Age of Smart IoT

The Internet of things (IoT), as the name suggests, is to connect all items through the network to realize the intelligent identification, information exchange and management of any object, person, time and place. Our understanding of the Internet of things is intelligent interconnection of things (IIoT), which reflects the meaning of “wisdom” and “ubiquitous network”, so we call it “intelligent Internet of things”, referred to as “intelligent Internet of things”. The essence of the intelligent Internet of things is to integrate the IT infrastructure into the physical infrastructure, that is, to embed and equip sensors into various objects such as power grid, railway, bridge, tunnel, highway, building, water supply system, dam, oil and gas pipeline, which are generally connected to form the so-called “intelligent Internet of things”, realizing real-time, intelligent and dynamic management and control.

The future of intelligent Internet of things is very broad, it will greatly change our current way of life. Our future will be an intelligent world, which will be widely used in intelligent transportation, environmental protection, government work, public safety, safe home, intelligent fire protection, industrial monitoring, elderly care, personal health and other fields. This technology will develop into a high-tech market with a scale of more than one trillion yuan.

Today's manufacturing industry is also facing a new round of technological revolution, intelligent manufacturing will be the development trend of the whole manufacturing industry. In this regard, Germany first put forward the idea of industry 4.0, which represents the arrival of the fourth industrial revolution. As an important part of the manufacturing industry, the injection molding industry should also follow the trend, seek breakthroughs and focus on the development of injection molding industry 4.0.

Injection molding industry 4.0 takes intelligent manufacturing as its core. Its idea is to deeply integrate the traditional injection molding industry and information communication technology, integrate information technology into the whole manufacturing process, manufacturing products and production equipment, and can real-time feedback and monitor the operating parameters of products and equipment, and optimize the whole manufacturing process.

In injection molding industry 4.0, the most important link is intelligent production. Intelligent production is a kind of “responsible” and “targeted” production activities. The so-called “responsible” refers to the use of advanced sensor technology (such as visual inspection technology), real-time feedback product information on the assembly line, whether the product meets the requirements, where there are defects and other information can be transmitted to the control headquarters, so as to detect defective products and timely adjust the process, so that the normal production of products; The so-called “targeted” refers to fully follow the requirements of customer personalized customization, according to the product's “label” (product customization information) automatically personalized, small batch production.

In the injection molding industry, the production process of products includes the processing and transportation of raw materials, injection molding, product removal,

automatic flow, follow-up processing (different products), etc. Therefore, the specific performance of intelligent production in the whole injection molding process is as follows.

(1) Highly automated integration

Injection molding machine peripheral should be equipped with a number of automatic equipment, such as automatic feeding system, manipulator, automatic assembly line, etc. All peripherals should follow two principles: reduce labor intensive and repetitive labor; in order to improve the quality of products, production efficiency and personalized production needs.

(2) Application of RFID Technology

Through radio frequency identification (RFID), raw materials, raw material processing equipment and molds can be encoded, and the collected information can be transmitted to the control system of injection molding machine. That is to record and connect all the information of the whole process from raw materials to finished products.

(3) Intelligent equipment

- ① The injection molding machine should be highly intelligent As the main equipment of injection molding industry, plastic machine should integrate advanced sensing technology to monitor product information and machine operation information in real time. At the same time, the injection molding machine should have a high degree of communication ability, be able to integrate the information of peripheral equipment, and can carry out intelligent process adjustment.

In addition, the injection molding machine should also transmit the collected information (including its own information, peripheral equipment information, product information) to higher intelligent systems, such as the Manufacturing Execution System MES.

- ② Peripheral equipment has a certain degree of intelligence Peripheral equipment assisted injection molding products, it should have a certain information receiving ability, automatic adjustment ability, and information feedback ability. The peripheral auxiliary equipment shall be able to automatically adjust the required process for different products and molds, and transmit the process condition data to the injection molding machine or other integrated controllers in real time.

(4) Communication of information

Injection molding industry 4.0 requires real-time, fast and accurate information communication among raw materials, equipment, products and control systems. The specific performance is: information communication between injection molding machine and peripheral equipment and raw materials; Information communication between injection molding machine and MES; Information communication between

product feedback information and injection molding machine or MES system; information communication between ERP and MES.

(5) Integration of information

Injection molding machine, peripheral equipment and product information need to be integrated in one or more controllers to facilitate operation, viewing and monitoring.

(6) Intelligent response to feedback information

Establishing a large database of equipment abnormalities and product defects. When the operation parameters of a certain equipment are abnormal, it should be able to quickly and intelligently analyze the reasons, adjust the operation parameters or stop the machine alarm by itself, and send the information to the manufacturing execution system (MES) and management system (such as ERP) to adjust the order and delivery time in time.

When the defect detection rate of a product increases, it should be able to quickly check whether the process parameters of each link deviate from the set tolerance, whether the equipment operation is abnormal, and whether the material batch is replaced in the whole production process from raw materials to finished products. The information can be summarized and analyzed intelligently, and the process parameters can be adjusted intelligently, or summarized into a report for technicians to quickly find out the causes and make correct response.

Secondly, on the basis of realizing intelligent production of injection molding, we can think about building an intelligent injection molding factory.

The intelligent injection molding plant requires full exchange of information. All information collected by the injection molding machine control system, including the information of the injection molding machine itself, raw material information and peripheral equipment information, can be transmitted to higher-level control systems, such as MES.

Through the MES system, it can monitor, view and operate all the equipment in the injection molding workshop, and track the operation and process parameters of all the equipment in the whole process from raw materials to finished products in an orderly way. When there are problems in product production, it should be able to quickly trace the source and find out the causes. In the intelligent injection molding plant, MES and ERP should fully exchange information and establish a strong physical information network (CPS).

The plan executor can arrange the production status of the order reasonably through the real-time information of the injection molding machine in the workshop (stop production status, fault status and running status). When there is an emergency in the workshop (such as machine failure), be able to adjust the production plan in time. The business department can evaluate the order quantity and delivery time by checking the production status of workshop equipment.

In this way, the problem of information isolation between business department and production department is well solved.

For injection molding equipment suppliers, they should consider using Internet technologies such as big data and cloud services to lay out intelligent service network,

monitor equipment operation status in real time, and inform customers whether the equipment needs maintenance in time, so as to realize intelligent service.

At present, injection molding manufacturers such as Arburg, Krauss-Maffei and Engle have launched their own industrial 4.0 solutions. Great progress has been made in intelligent detection, intelligent control, information recording and tracking, data sharing and remote maintenance.

Injection molding industry 4.0 is still in its infancy, still needs to break through many technical barriers, and more new ideas and ideas need to be integrated. But its grand vision is worth exploring and trying by the knowledgeable people in the injection molding industry. I believe that with the continuous development of industry 4.0 and the arrival of the era of intelligent Internet of things, 3D copying technology and mold manufacturing technology will be more intelligent, more efficient and more convenient.

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Index



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A

Adaptive blister mold, 297, 298
Air bubble, 132, 187
Albino, 274
Angle of repose, 224, 225

B

Barrier type screw, 35, 168
Bulk density, 223, 224

C

Cavity, 1, 6–8, 10, 11, 13, 20, 28, 34,
38–40, 42–45, 49, 53, 55–58, 60, 61,
63, 64, 68, 72–74, 76, 84, 95, 98,
100–103, 110, 112–115, 137, 138,
147–149, 158–160, 163, 176, 185,
188–190, 192, 200, 209, 217, 230,
231, 237–239, 242, 243, 245–250,
254, 255, 257–262, 264–272, 274,
277, 278, 280, 295–297
Clamping force, 27, 40, 50, 57, 59, 61, 145,
146, 163, 164, 175–178, 189, 195,
196, 258, 259, 264
Coefficient of thermal expansion, 222
Color difference, 273, 274, 276
Cooling, 1, 8–11, 26, 27, 33, 34, 38, 40, 49,
51, 57, 61, 62, 64, 71–73, 76, 90, 91,
104, 115, 118, 119, 121, 125, 128,
137, 138, 141, 143, 147, 158–160,
188, 189, 192, 193, 200, 216, 217,
219, 222, 229, 230, 236, 239, 242,
243, 245–247, 251, 255, 258, 261,
262, 264, 265, 270, 277–280, 282,
288, 290, 294

Crystallization, 37, 38, 61, 157, 187, 220,
240–244, 262

D

Demolding, 8, 10, 11, 37–39, 49, 56, 160,
211, 237, 238, 243, 274–277, 280,
293
Die cavity pressure, 282
Die filling, 260, 261, 265, 268
Diffusion bonding, 104
Dynamic pressure, 102, 103, 160, 163

E

Ejector mechanism, 9
Embrittlement, 252, 279, 280
Expansion force, 44, 176

F

Feature modeling, 20–22
Field synergy screw, 169
Filling, 3, 8–10, 13, 26, 27, 32, 35, 38, 45,
58–61, 64, 72, 76–78, 93, 95,
103–107, 115, 116, 121, 157–160,
193, 207, 208, 210–212, 216, 217,
230, 231, 239, 240, 245–250,
252–255, 257, 259–268, 271,
275–277, 280, 282
Fitted mold, 174
Foaming injection, 10, 56, 65–67, 143
Free forming, 94
Friction factor, 225
Fused deposition modeling (FDM), 4, 34,
53–56, 83–86, 93, 169

G

Gas-assisted injection molding (GAIM),
10, 60, 61
Gating halo, 267

H

Heating, 10, 11, 33, 34, 40, 43–45, 53, 54,
64, 71–75, 86, 107, 115, 119, 127,
132, 138, 141, 146, 147, 150, 152,
153, 161, 169, 172, 174, 185, 200,
206, 219, 222, 229–231, 235, 236,
240, 244, 259, 269, 271, 273, 279,
282, 293, 300
Hot runner, 42–46, 49–53, 72, 95, 101, 125,
269

I

Injection, 1, 6, 8–10, 12–14, 26–28, 34, 35,
38–52, 56–80, 92, 94, 108, 137–141,
143–169, 171–177, 179, 181–183,
185–197, 200, 201, 205–209,
212–214, 216, 217, 223, 228–237,
239–282, 285, 286, 288, 290,
292–296, 302–305
Injection compression molding (ICM), 10,
56–60
Injection molding technology, 7, 10, 40, 42,
56, 70, 77, 92, 137, 146, 158, 191
Insulation material, 44, 220
Intelligent injection molding plant, 304

L

Laminated objected manufacturing (LOM),
4, 53, 83, 84, 89–91, 293

M

Magnetic fluid, 296–300
Melt, 8, 9, 26, 27, 34–36, 38–41, 44, 45, 47,
49, 50, 53, 55, 57, 60, 61, 64, 66–70,
72, 84, 85, 89, 93–96, 98, 100–107,
109–116, 123–125, 128–132, 137,
138, 147–153, 155–160, 162–165,
169, 173, 174, 188, 190, 192, 193,
200, 208, 210, 211, 214–218,
227–231, 240, 242–248, 250, 255,
258–272, 274–278, 280, 282, 289,
294
Melt differential, 70, 94–98, 105, 122, 123,
129–133

Melt flow, 28, 59, 101, 110, 112, 131, 159,
173, 210, 215, 217, 239, 245, 248,
255, 257, 264, 265, 270, 276

Melt flow rate, 98, 99, 101–103, 110, 112,
113, 208, 217, 231, 232

Melting point, 54, 84, 85, 206, 217, 218,
225, 244, 285, 292, 293

Melt limit, 217, 218

Melt pumps, 71

Micro-droplet jetting (MDJ), 4, 84, 92–94,
107–109

Microinjection, 10, 56, 69, 70, 173

Mold, 1, 2, 5–11, 13, 14, 20, 22, 24, 26–28,
30, 31, 34, 37–45, 48–53, 56–65, 67,
68, 70–76, 83, 84, 86, 87, 91, 137,
138, 140, 143, 144, 146–151,
157–161, 163, 173–177, 179–182,
184, 185, 188–190, 192, 195–201,
206, 207, 209, 212, 216, 217, 220,
230, 231, 236–255, 257–259,
261–280, 282, 285–298, 303, 305

Multi-component injection, 10, 56, 67, 68,
143

N

Nano injection molding (NMT), 10, 56,
77–79

Natural balance, 259

Nozzle, 9, 34, 39, 41–49, 53, 54, 56, 59–61,
65, 68, 84, 85, 91, 92, 94–96,
101–106, 109–116, 119–122, 125,
127, 131, 132, 138, 141, 147, 149,
161, 162, 164, 172–175, 185, 189,
190, 217, 231, 236, 244, 253, 254,
256–258, 262, 264, 267, 269,
271–273, 276, 277, 279

O

Orientation, 26, 27, 37, 38, 157, 159, 189,
239, 240, 243, 245, 246, 248, 275,
277, 280–282

P

Parametric design, 20

Physical pre-foaming, 66

Plasticized, 9, 94, 95, 100, 132, 146, 153,
155, 161, 163, 164

Point cloud, 17, 19, 20, 29–32

Pouring system, 42

Precision 3D copier, 190

PVT characteristic, 41, 42, 200, 223

PVT curve, 186–188

R

Rapid heating cycle molding (RHCM), 71

Residual pressure, 160

Residual stress, 9, 10, 37, 38, 49, 59, 158,
160, 189, 219, 239, 240, 246, 252,
275, 276, 278–282

Resin transfer molding (RTM), 10, 56, 62,
63

Rheological equilibrium, 46

S

Scorch marks, 268

Selective laser sintering (SLS), 4, 83, 84,
86, 87, 91, 289, 291–293

Separate screw, 168

Sequential injection, 57, 68

Silverstripe, 271

Specific volume, 41, 158, 159, 186–188,
190, 200, 218, 219, 222

Spray marks, 264, 265

Stacked injection, 34, 289

Static pressure, 102, 103, 160

Stereo lithography apparatus (SLA), 4, 53,
83, 84, 87–89

Structured light non-contact scanning, 18

T

3D copying technology, 1, 2, 7, 12, 17, 34,
37, 94, 285, 298, 305

Three-dimension printing (3DP), 4, 83, 84,
91, 92

3D printing technology, 1, 2, 4–6, 12–14,
17, 33, 34, 84, 85, 92, 94, 286, 288,
290, 293, 294, 298

Tie rod, 175, 178, 180, 181

Transformation point temperature value,
259

Triangular gridding, 105, 123

Two-plate injection molding machine, 143,
195

V

Visualization, 247–249, 251–256

W

Warpage deformation, 90, 104, 105, 115,
246, 278, 280

Water-assisted injection molding (WAIM),
56, 60, 61

Wave trace, 255, 266

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